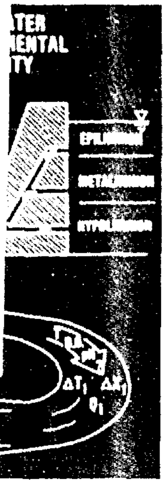
(2)

US Army Corps of Engineers

AD-A218 670



ENVIRONMENTAL IMPACT RESEARCH PROGRAM

TECHNICAL REPORT EL-90-2

HABITAT FACTORS IN TAILWATERS WITH EMPHASIS ON PEAKING HYDROPOWER

by

James A. Gore, John M. Nestler

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

and

James B. Layzer

Tennessee Cooperative Fishery Research Unit
US Fish and Wildlife Service
Cookeville, Tennessee 38501

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

January 1990

Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under EIRP Work Unit 32494

ENVIRONMENTAL LABORATORY

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION / DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report EL-90-2	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION See reverse. — 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) See reverse.	7b ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION US Army Corps of Engineers — 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO — PROJECT NO — TASK NO — WORK UNIT ACCESSION NO: EIRP 32494

11 TITLE (Include Security Classification)
Habitat Factors in Tailwaters with Emphasis on Peaking Hydropower

12 PERSONAL AUTHOR(S)
Gore, James A.; Nestler, John M.; Layzer, James B.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final report	FROM ______ TO ______	January 1990	

16 SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Habitat factors	PHABSIM
			IFIM	Tailwater
			Instream flow	Tailwater ecology

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes habitat conditions in tailwaters downstream of Corps of Engineers' dams, with emphasis on peaking hydropower effects, by summarizing literature information, updating findings made previously under the Environmental and Water Quality Operations Studies Program, and presenting preliminary results of field work performed as part of this research effort. Habitat conditions in tailwaters are presented at two different levels of resolution. First, in general terms, physical and chemical conditions in unregulated streams and in tailwaters downstream of surface- and deep-release projects are compared and contrasted. Many of the generic impacts associated with peaking hydropower operation are also described. Second, the detailed effects of peaking hydropower operation are described for benthos and selected fishes using concepts in the Instream Flow Incremental Methodology (IFIM). These studies were performed on the Caney Fork River

(Continued)

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code) — 22c OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

6a. NAME OF PERFORMING ORGANIZATION (Continued).

USAEWES, Environmental Laboratory;
US Fish and Wildlife Service

6c. ADDRESS (Continued).

3909 Halls Ferry Road, Vicksburg, MS 39180-6199;
Tennessee Cooperative Fishery Research Unit, Cookeville, TN 38501

19. ABSTRACT (Continued).

downstream of Centerhill Dam, Tennesse. Based on results of the first phase of field studies, methods are suggested for using a modified IFIM for determining the downstream effects of different release schedules, for assessing downstream effects of upgrading or retrofitting hydropower, and for determining flows necessary to maintain or protect downstream aquatic biota.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

PREFACE

This report was prepared by the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. This study forms part of the Environmental Impact Research Program (EIRP), Work Unit 32494, "Assessing Effects of Reservoir Operation on Downstream Aquatic Resources." The EIRP is sponsored by Headquarters, US Army Corps of Engineers (HQUSACE), and is assigned to WES under the management of the EL. Dr. Roger T. Saucier, EL, is the Program Manager for the EIRP. The HQUSACE Technical Monitors for EIRP are Dr. John Bushman, Dr. Dave Buelow, and Mr. Dave Mathis.

This report was written by Drs. James A. Gore, John M. Nestler, and James B. Layzer. Dr. Gore was assigned to WES under an Interagency Personnel Agreement between WES and Tulsa University. Dr. Layzer is the Assistant Leader of the US Fish and Wildlife Service Tennessee Cooperative Fishery Research Unit at Cookeville, TN. This report was prepared under the direct supervision of Dr. Nestler, EL, and under the general supervision of Mr. Mark S. Dortch, Chief, Water Quality Modeling Group (WQMG), EL; Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, EL; and Dr. John Harrison, Chief, EL. The inhouse technical review was performed by Ms. L. Toni Schneider and Mr. Tom Cole, both of WES, and Dr. Robert Milhous of the US Fish and Wildlife Service. Mr. Kyle Bertrand prepared graphics for this report, and Ms. Schneider provided computer support for the simulations. This report was edited by Ms. Lee T. Byrne, Information Technology Laboratory, WES.

The authors thank Mr. Jim Sharber of the US Army Engineer District, Nashville, for his assistance in and support of these studies.
Dr. Robert Milhous of the National Ecology Center provided modifications to the PHABSIM code that made the time-varying analyses possible.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

This report should be cited as follows:

Gore, James A., Nestler, John M., and Layzer, James B. 1990. "Habitat Factors in Tailwaters with Emphasis on Peaking Hydropower." Technical Report EL-90-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

HABITAT FACTORS IN TAILWATERS WITH EMPHASIS ON PEAKING HYDROPOWER

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers (CE) develops and manages water resources in a manner consistent with environmental quality following Congressional and Administrative laws and policies. That is, the CE considers and seeks to balance the developmental and environmental needs of the Nation.

2. As part of its role in the development of water resources, the CE operates reservoir projects to fulfill authorized project purposes including, but not limited to, flood control, water supply, navigation, and power generation. Operation of reservoir projects can considerably alter downstream river reaches or tailwaters. Reservoirs may modify flow, channel morphology, water temperatures, and water quality thereby significantly altering the downstream aquatic ecosystem. Development of water resources in a manner consistent with environmental quality considerations requires an understanding of tailwater ecology, both to develop defensible assessment methods and to devise methods for ameliorating or avoiding the negative downstream impacts of reservoir operation.

3. Tailwater ecosystems are characterized by complex physical, chemical, and biological interactions. The aim of this report is to identify and describe the dominant factors that structure tailwater ecosystems and to present some approaches for assessing the impacts of reservoirs, particularly peaking projects, on downstream aquatic biota. With this information, CE scientists will be better able to predict and describe downstream changes in energy pathways, community structure, and longitudinal zonation resulting from impoundment. This knowledge is crucial to maintaining and preserving downstream aquatic resources.

4. Stream and river ecosystems have been intensively studied in recent years to determine factors that structure and control their dynamics. This information has been used by stream ecologists to develop conceptual templates upon which further knowledge can be organized or expanded, ultimately leading

to the development of defensible assessment methods to guide water resources development.

5. Two major and often competing concepts have emerged to explain the ecology of running waters: the River Continuum Concept (RCC) (Vannote et al. 1980) and the Hydraulic Stream Ecology Concept (HSEC) (sensu Statzner and Higler 1986; Statzner, Gore, and Resh, in press). Either concept may be valid depending upon the problem being addressed. Impact assessment at a general ecosystem or community level is probably best addressed using the RCC. Impact assessment or management alternatives of specific operational or project alternatives are best determined using the HSEC since the RCC lacks an adequate level of hydraulic resolution.

River Continuum Concept

6. The RCC tends to emphasize ecosystem level processes, such as changes in trophic state as related to increases in stream order. It provides a good theoretical framework for the underlying chemical and biological dynamics that lead to species replacement (zonation) along the length of a river. However, use of the RCC on regulated streams was difficult since it was developed and applied on unregulated streams.

7. Ward and Stanford (1983) have applied the ideas within the RCC to tailwaters by proposing the Serial Discontinuity Concept (SDC) to explain the ways that impoundments affect the continuum. Ward and Stanford propose that impoundments (chiefly deep release structures) act to "reset" the tailwater conditions to a chemical and community structure found in lower order (more headwater) streams. That is, since most impoundments occur in medium- to high-order river reaches, the effect of the impoundment is to return the tailwater areas to conditions in which primary production (periphyton) drives the energy dynamics rather than fine particulate organic matter (FPOM). Surface release dams also produce resetting since larger particulates (in the form of plankton and seston) are released into the tailwaters. Thus, collectors and filterers of the largest categories of particulate organic matter (POM) dominate these tailwaters. The recovery distance (return to conditions predicted by the RCC) is determined by location of the dam along the length of the river and the number and interval of impoundments on the river system. The condition of organic input and the way that it is available and utilized

are basic criteria for community structure and development. Figure 1 illustrates how impoundment affects the distribution of aquatic biota in a stream ecosystem. In all cases, the density of Ephemeroptera increases with downstream distance from the reservoir. Densities were highest in the river upstream of the reservoir.

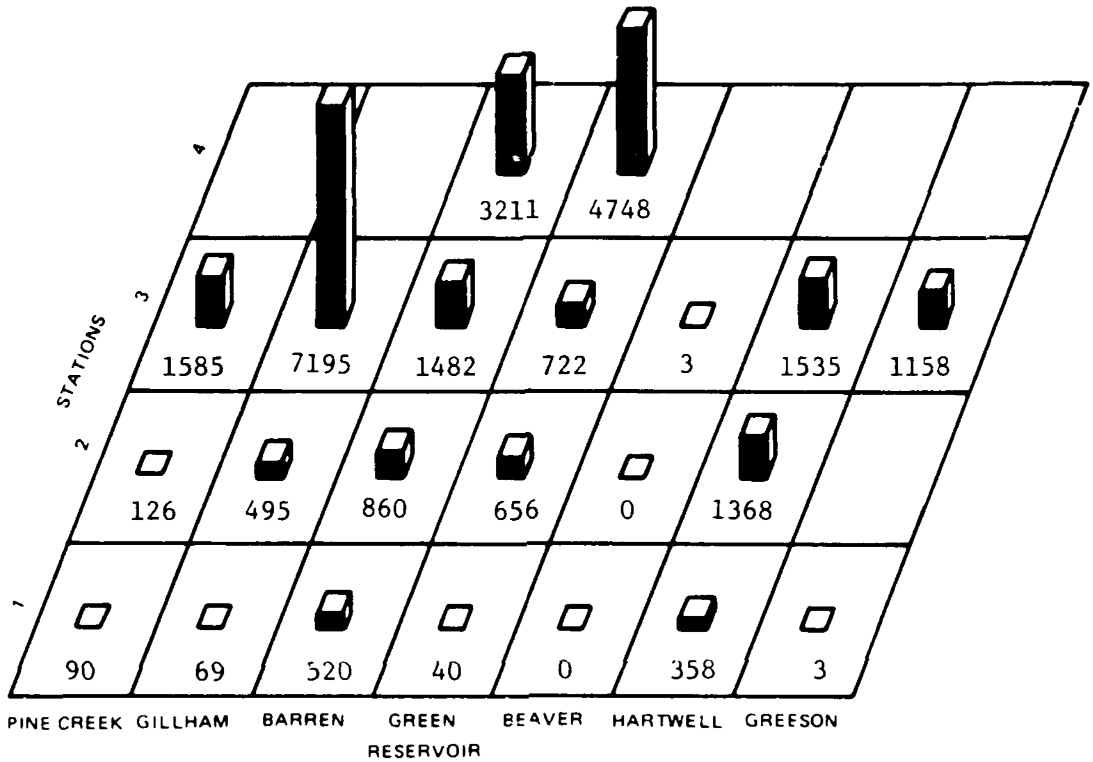


Figure 1. Example of changes in density (number/square metre) of Ephemeroptera (mayflies) at varying distances downstream from CE reservoirs. Station 1 is located nearest the dam, and Station 3 is located farthest downstream. Station 4 is located upstream of the reservoir (Nestler et al. 1986b)

8. Detailed analyses of hydraulic conditions are usually absent or stated in very general hydrologic terms (mean depth or flow) in both the RCC and the SDC. Consequently, there is no pathway using the RCC to predict changes in POM input, community dynamics, or functional organization (in terms used by the RCC) as a result of changes in discharge rate.

Hydraulic Stream Ecology Concept

9. The HSEC emphasizes the controlling influence of stream hydraulic variables, such as depth, velocity, and shear stress, as factors that

determine the ecology of running streams. Although developed before the HSEC was [illegible]ned, the Instream Flow Incremental Methodology (IFIM) (Bovee 1982) of the [illegible] Fish and Wildlife Service is based on many of the precepts contained in the HSEC.

10. The RCC has established a basic framework for biotic distributions as a function of the pattern of organic matter (both dissolved and particulate) from stream headwaters to stream mouth. The processing and reprocessing of allochthonous and autochthonous inputs determine the functional composition (shredders, grazers, filter-feeders, collectors, and predators) of the benthic communities along the length of a river and, in turn, the functional composition (invertivores, piscivores, and planktivores) of fish assemblages. This concept has been criticized by Winterbourn, Rounick, and Cowie (1981), who found these relationships lacking in New Zealand, and by King et al. (in press), who found only slight correlations in some rivers in South Africa. In spite of criticisms of the RCC, it is a particularly useful reminder that ecosystem level processes are important considerations in describing and managing the downstream environmental quality impacts of dams

11. Most recently, criticisms of the RCC have indicated that a stronger consideration of physical processes (hydrological and geomorphological changes) is basic to the environmental factors or template which influences the longitudinal zonation of stream and river biota (Statzner and Higler 1985, 1986). More recently, Statzner, Gore, and Resh (in press) point to the strong influence of hydraulic interactions, particularly near substrate conditions such as shear stress, as major factors in habitat preference of all trophic levels in running water ecosystems. Statzner (1987) points to considerable evidence that abiotic conditions (the severity of physical stress) largely determine distributions of aquatic biota in running water. Thus, prediction of changes in flow should also reflect the changes in community composition of the tailwater ecosystem. Only organisms that move with the water column are immune to these flow influences; however, even they will encounter and must be adapted to influences introduced from variations in turbulence. The HSEC is further supported by Scarnecchia (1988), who found that morphometric information which defines streamlining could be used to predict the composition of fish communities in channelized (where shear forces are higher) and unchannelized streams.

12. Both the SDC and the HSEC strongly indicate that factors influencing biotic distributions in streams are altered by dams. The objective of this report is to summarize current knowledge on the impacts of reservoir operation on tailwater ecosystems with particular emphasis on unique aspects of peaking hydropower operations. Current knowledge is presented at two levels. First, in a manner conceptually similar to the RCC, impacts of impoundment are presented at an ecosystem level. In this level, qualitative information is presented to generally characterize the impacts of different design or operational alternatives. This information is presented in Part II, entitled "General Impacts of Impoundments," and Part III, entitled "Impacts of Peaking Hydropower Operation."

13. At the second level, in a manner conceptually similar to the ideas in the HSEC, detailed methods are presented for assessing the impacts of peaking hydropower operation on target aquatic biota. The methods are based on a modified IFIM. The IFIM allows assessment of impacts on habitat of aquatic biota using many hydrologic and hydraulic principles. The findings of Statzner, Gore, and Resh (in press) suggest that precise descriptions of physical habitat conditions, in conjunction with habitat suitability criteria, such as occur in the IFIM, offer a management tool which is a reasonable blend of the biological theory of the RCC and the hydraulic precision required of a tailwater assessment/management tool. Information on the second level is presented in Parts IV, V, and VI.

PART II: GENERAL IMPACTS OF IMPOUNDMENT

Background

14. Identification of the downstream environmental effects of peaking hydropower operation is usually confounded by two factors. First, the downstream effects of peaking hydropower operation are partly determined by the impacts associated with reservoir projects in general. These effects include seasonal alterations in water quality, alteration in downstream sediment transport, and seasonal modifications in the yearly hydrograph. Second, the downstream effects of peaking hydropower operation are confounded with the effects of deep release since most peaking projects have only deep-release capability. Studies of the effects of peaking projects may incorrectly relate effects of deep release to those caused by peaking operation. Consequently, the first requirement in understanding and minimizing the impacts of peaking hydropower operation is to first understand the general impacts of impoundment.

15. The alteration of receiving stream ecosystems by reservoir operation has received considerable attention in recent years. A number of general summaries of regulated river and stream research have been produced (Baxter 1977; Cairns, Benfield, and Webster 1978; Baxter and Glaude 1980; Walburg et al. 1981; and Brocksen et al. 1982). This interest in impoundment effects has culminated in the international regulated stream symposia (Ward and Stanford 1979, Lillehammer and Saltveit 1984, and Craig and Kemper 1987) and the publication of a major journal, Regulated Rivers, and important texts (Petts 1984; Gore and Petts, in press). Among CE documents, Nestler et al. (1986b) have summarized specific effects related to CE project operations. All of these summaries point to the same basic suite of conditions that impact impounded rivers: alteration of thermal regime, water quality, organic and inorganic loads, and changes in channel geometry induced by increased stream power of the release waters. The general impacts of reservoirs and the effects of release depth are presented and discussed in the following section to present necessary background information to allow a fuller understanding of the effects of peaking hydropower operation.

Downstream Impacts of Impoundment

16. In general, the degree and extent of downstream environmental impacts are related to the classification of the reservoir, which, in turn, determines quantity and timing of releases. Reservoirs can be broadly classified as either peaking hydropower or nonhydropower projects (in terms of many environmental impacts, baseload projects resemble nonhydropower projects).

17. To understand the effects of reservoir releases, it is first necessary to understand how impounded waters differ from running waters. Major changes that occur in impounded waters are generally related to the hydraulic transition that occurs as river water flows into the headwaters of a reservoir. Reduced mixing in reservoirs, in contrast to highly mixed riverine flows, facilitates sedimentation and seasonal reservoir stratification. This, in turn, causes reservoir outflows to differ substantially from the reservoir inflows.

18. Physical and chemical changes in tailwaters caused by reservoir project operation are primarily determined by the volume and timing of releases, the chemical and biological conditions within the reservoir at the depth from which the water is withdrawn, and the composition and shape of the stream channel and banks. The concentration of dissolved gases in water released from the reservoir is further altered during passage through the project outlet structure and stilling basin. The water quality of the releases can be further modified in the tailwater by ground-water inflow, tributary streams, biogeochemical processes (chemical transformations, photosynthesis, decomposition, etc.), and atmospheric influences.

19. The principal water quality parameters of concern downstream from a reservoir are temperature, POM, dissolved oxygen (DO), metals (iron and manganese), and nutrients associated with reduced oxygen concentrations. Figure 2 presents the concentrations of ammonia, total iron, and total manganese in a deep-release reservoir tailwater. These constituents are usually found in low concentrations in unregulated rivers. The concentrations of these constituents in the tailwater are directly related to the progression of chemical stratification in the upstream reservoir. Modifications in daily and seasonal temperatures caused by operation of a reservoir project are primarily determined by the depth of withdrawal, seasonal stratification

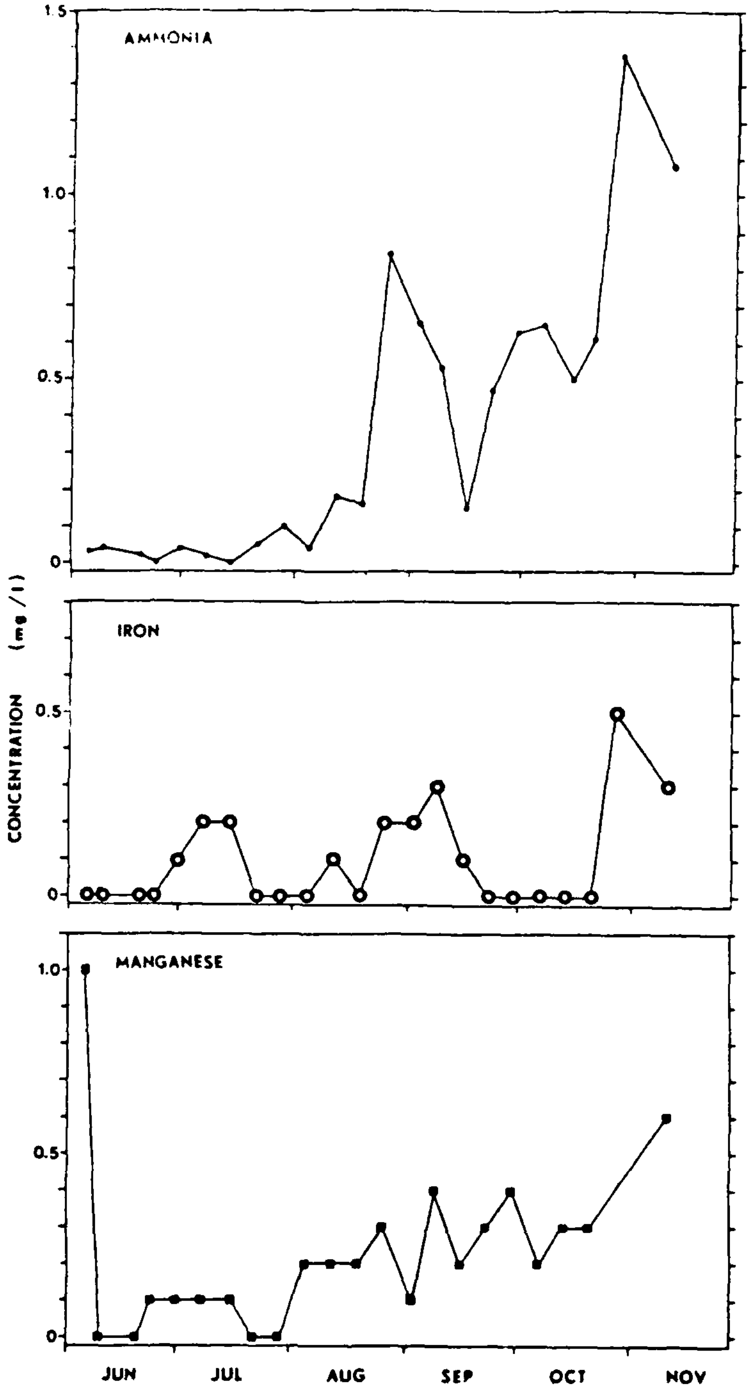


Figure 2. Concentrations of ammonia, total iron, and total manganese in the immediate tailrace of Green River Lake. Samples taken weekly from June through November of 1980 (Walburg et al. 1983)

patterns within the reservoir, and the timing, frequency, and discharge rate of withdrawals. Relative temperature alterations caused by deep release versus surface release are discussed in detail in the following section (paragraph 24). In general, seasonal temperature changes are suppressed and delayed in tailwaters below unstratified reservoirs because the time required to cool or warm a large volume of impounded water is significantly longer than the time required to cool or warm the smaller volume of water in an unregulated stream. Naturally occurring diurnal temperature fluctuations observed in unregulated streams are suppressed in tailwaters, especially near the reservoir outflow.

20. Modification of preimpoundment seasonal temperatures by a reservoir project may have a pronounced effect on aquatic biota since specific temperatures may terminate or initiate different life stages. For example, in unregulated streams and rivers, spawning by many species of fish is initiated, at least partially, by warmer, springtime water temperatures. Delayed warming downstream from a reservoir project will cause a delay or possible total postponement of spawning by some species of fish in a tailwater. Altered seasonal water temperatures also interfere with normal progression of life-history stages of some species of aquatic insects (Ward 1974, 1976). If temperature alteration is particularly severe, desirable aquatic insects (from a fisheries standpoint), such as mayflies, caddisflies, and stoneflies, may be replaced by groups such as black flies, midges, and oligochaetes. The loss of the thermal cue normally provided by the rapid increase in spring water temperatures results in the inability of many stream macroinvertebrates to complete their life cycles. Zones of relative thermal constancy below reservoirs often contain communities dominated by species that do not require thermal cues for egg hatching, breaking diapause, or maturation and emergence. For example, Gore (1980) found tailwater areas to be dominated by sphaeriid clams and elmid beetles, whereas Gore and Pennington (1988) found chironomid species to be dominant. These alterations in the benthic community may have a direct impact upon the aquatic foodchain by altering the flow of energy and nutrients available for higher trophic levels. Figure 3 illustrates how impoundment affects diversity and abundance of the benthic community in tailwaters. Note the reduction in species diversity of the benthic community in these two tailwaters.

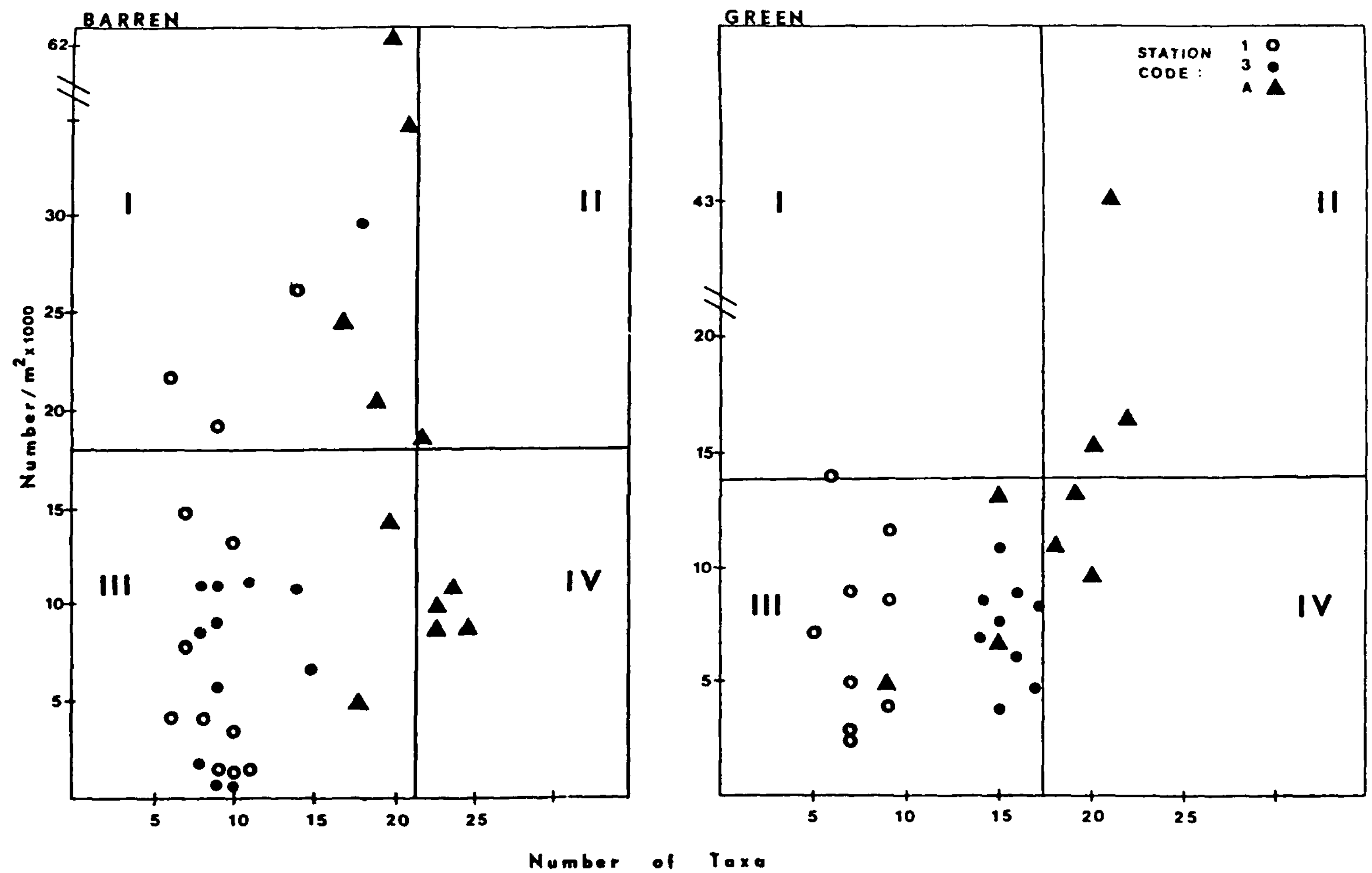


Figure 3. Ordination of the numbers of taxa and total numbers/square metre of macroinvertebrates collected with a Hess sampler within 1 km of the dam (Station 1), within 22 km of the dam (Station 3), and in the river upstream of impoundment (Station A) for Barren River Lake and Green River Lake, Kentucky (Walburg et al. 1983)

21. Food webs differ between tailwaters and unregulated streams. In most large streams, the food chain is based primarily on allochthonous POM such as leaves, bark, and detritus washed in from the watershed (Vannote et al. 1980). Many benthic organisms shred and ingest this material along with the associated bacteria and fungi. These benthic organisms are then eaten by many species of fish, either directly from the substrate or when the benthic organisms enter the "drift" (a phenomenon in which benthic organisms either voluntarily or accidentally leave the substrate and are swept downstream with the current either to reattach farther downstream or to emerge). However, most allochthonous material settles out within the reservoir (if the hydraulic residence time is sufficiently long) and is largely unavailable in the tailwater ecosystem, although at high flows inundated streamsides provide detritus, terrestrial vegetation, and terrestrial invertebrates to the tailwater as in natural streams. The unavailability of allochthonous material, in combination with seasonal temperature alterations, causes a shift in the composition of benthic macroinvertebrate communities in tailwaters. Figure 4 illustrates how impoundment can alter the composition of the benthic community in tailwaters. Note the depression of abundances of predators and shredders in the immediate tailwater and how the abundances increase in the more downstream reach (Station 3) and in the reach of the river upstream of the dam.

22. Patterns of abundance and distribution of fish are considerably altered in tailwaters from those observed in unregulated streams and rivers. Many tailwaters exhibit seasonal concentrations of fish to the extent that sport fisheries are developed and managed. A variety of site-specific factors cause fish to concentrate in the tailwaters of reservoir projects. Fish concentrate seasonally in tailwaters because dams may block upstream migration. At other times, some species of piscivorous (fish-eating) fish may congregate in the tailwater when prey fish are discharged from the reservoir. Additionally, fish appear attracted to tailwaters in winter because the reservoir releases are often warmer than unregulated rivers. A major source of increased fish abundance in tailwaters, particularly in the tailwaters of nonhydropower, flood-control projects, appears to be movement of fish from the reservoir into the tailwater. That is, reservoirs serve as a source of recruitment (Jacobs et al. 1985) for many of the fish found in the tailwater in addition to natural reproduction in the tailwater. Fish passage through

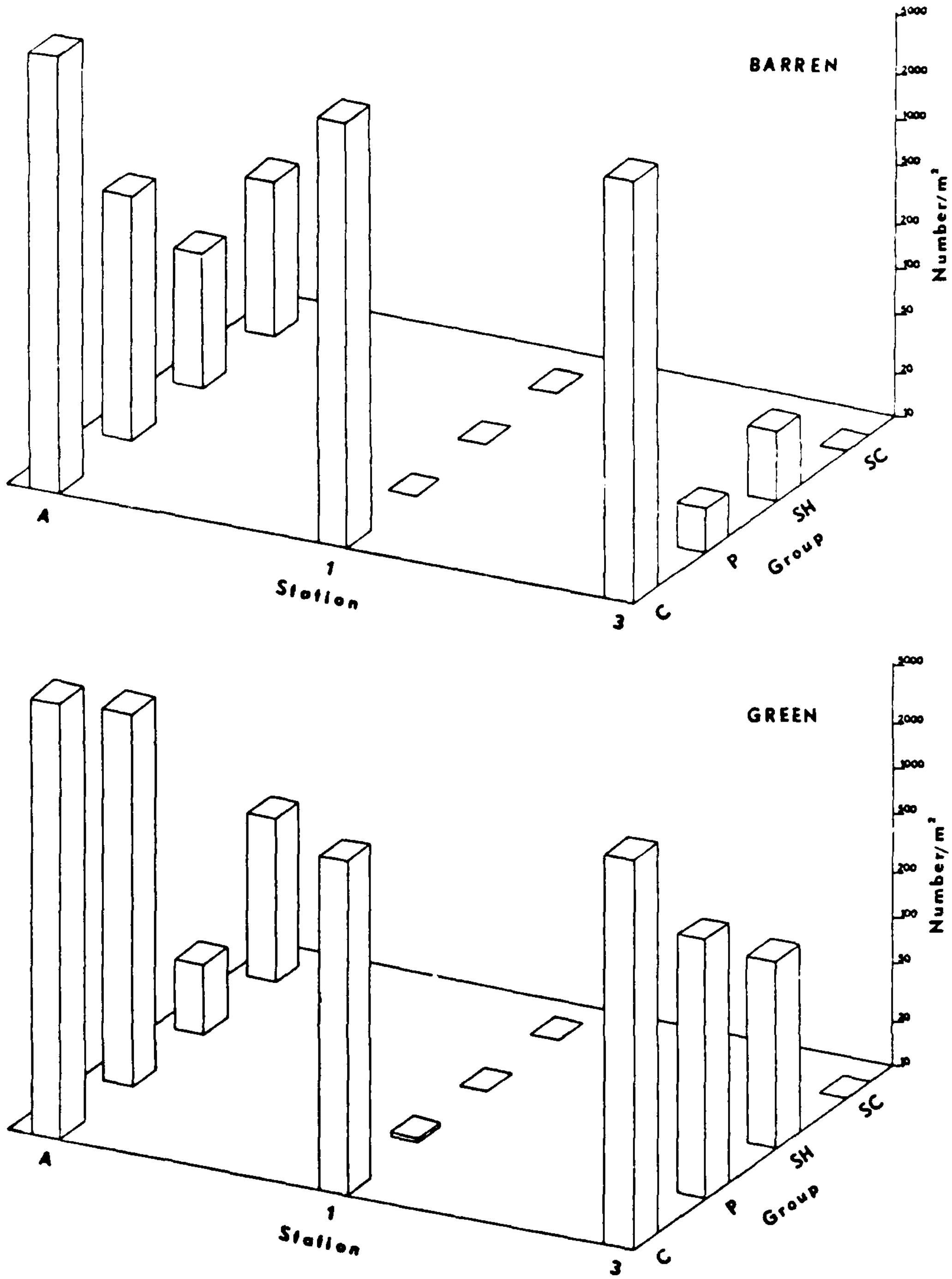


Figure 4. Distribution of macroinvertebrate functional feeding groups, including collectors (C), predators (P), shredders (SH), and scrapers (SC) at tailwater Stations 1 (approximately 1 km from dam) and 3 (approximately 22 km from the dam) and headwater station of the Barren and Green Rivers. Data collected by Hess sampler (Walburg et al. 1983)

the project or over the spillway can occur sporadically at any time of the year (e.g., summertime movement of striped bass through the turbines or springtime movement of walleye as they congregate to spawn on riprap on the face of a dam), but is generally most common during periods of destratification, particularly in the fall and winter when fish move into deeper water in the reservoir (and consequently nearer to the vicinity of the intakes) and the discharge rate is increased for flood-control operation. Natural reproduction does not appear to be an important source of recruitment in some formerly warmwater streams downstream from deep-release projects because coldwater releases interfere with successful spawning. Figure 5 presents the relative

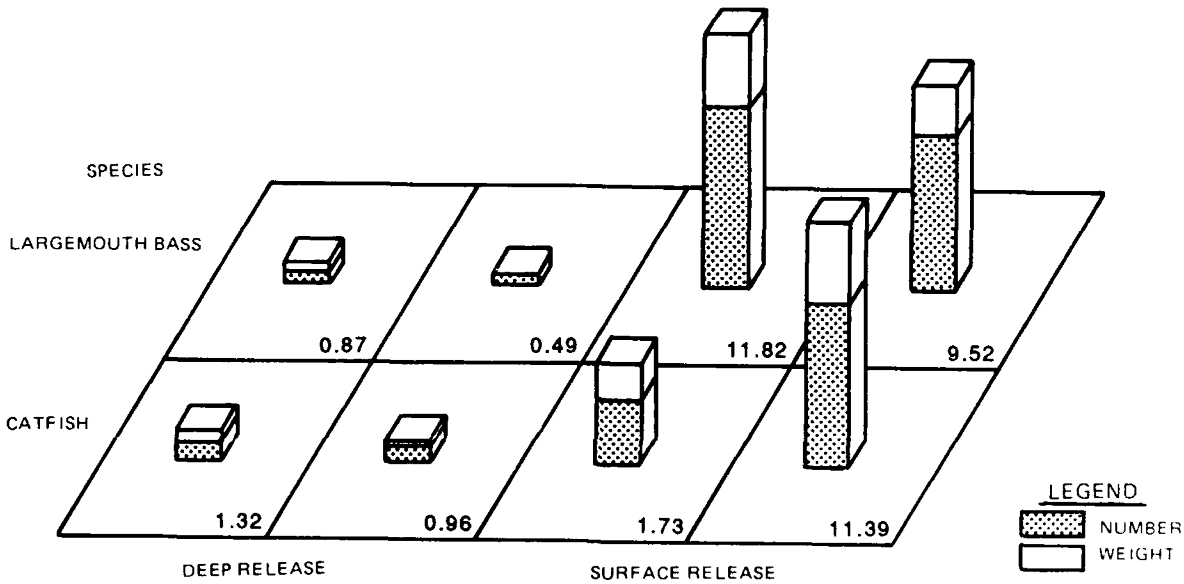


Figure 5. Mean relative biomass (kilograms per hour of electrofishing) and mean relative number (number per hour of electrofishing) of warmwater fish downstream from surface-release projects (Gillham Lake, Arkansas, and Pine Creek Lake, Oklahoma) and deep-release (Barren River Lake and Green River Lake, Kentucky) projects on formerly warmwater streams

abundances of two warmwater fishes in coldwater and warmwater tailwaters. Note the considerable reduction of abundances for both channel catfish (*Ictalurus punctatus*) and largemouth bass (*Micropterus salmoides*) in the coldwater tailwater (from Walburg et al. 1983).

23. Physical habitat in the tailwater is also altered as a consequence of reservoir operation. In an unregulated stream, the composition of the channel bed reflects the dynamic equilibrium between deposition and transport as sediment moves progressively downstream in the system. However, the presence of a reservoir disrupts the downstream movement of sediment by

capturing most suspended sediments and bed load. The sediment-poor waters released from deep release (especially hydropower) reservoirs are often of high potential energy. Thus, within a short distance from the dam, increased erosion and bank instability contribute sediments that often block or limit the use of preferred habitat and spawning areas downstream (Reiser, Ramsey, and Wesche, in press).

Surface Versus Deep Release Effects

24. Many reservoirs stratify chemically and thermally during some portions of the year. Thus, chemical and physical conditions in the reservoir may vary considerably from the surface to the bottom. Dams may discharge water from near the surface or from deep in the reservoir; in some cases, a blend of water may be released from various depths if the project has a selective withdrawal capability. The depth from which water is released from a stratified reservoir can be one of the most important factors determining the composition and abundance of tailwater biota. Surface-release projects generally do not release water of poor quality except, perhaps, immediately following reservoir destratification. Deep-release projects may discharge flows of poor quality if the reservoir is thermally stratified and the hypolimnion is anaerobic. Considerable improvement in the quality of releases may occur through reaeration as water passes through the outlet works of nonhydropower flood-control projects.

25. The relative effects of surface versus deep release on a stream or river are determined by the altitude and latitude of the project and the physical and chemical conditions within the reservoir at the depth of withdrawal. In the majority of cases, project altitude and latitude will determine the preimpoundment classification of affected river reaches as coolwater, coldwater, or warmwater streams. The aquatic biota found in each of these different systems vary considerably in their water quality tolerances and requirements.

Surface release on warmwater streams

26. Although algal blooms in the reservoir have, on occasion, resulted in short-term toxic effects in the tailwater, the effects of surface release on a warmwater stream are generally not detrimental unless gas supersaturation occurs. Supersaturation occurs when releases with entrained gas plunge into

deep pools in the tailwater. Hydrostatic pressure in the deep pool forces the entrained gas into solution. The gas gradually comes out of solution as the water proceeds through the shallower reaches of the tailwater. The gas may come out of solution within the bodies of aquatic organisms (caisson (gas bubble) disease, "the bends") causing embolisms and, perhaps, death (Fast and Holquist 1982).

27. The effects of altered water temperature and quality on tailwater biota caused by surface releases into a formerly warmwater stream are generally not serious (Walburg et al. 1981; Walburg et al. 1983). In terms of water quality only, releases from the surface of a reservoir are generally similar to the outflow of a natural lake. The major tailwater temperature alterations (delayed spring warming, increased summer water temperatures) have not been documented to harm tailwater aquatic biota. Poor release water quality is generally not a problem except immediately subsequent to reservoir mixing if the reservoir is chemically stratified. Consequently, many of the fish species found in the river before the project was built may still be found once the project is in place because conditions in the tailwater fall within the tolerance limits of many warmwater organisms (Walburg et al. 1983).

28. The benthic community in a formerly warmwater stream downstream from a surface-release project will exhibit a shift in composition. The tailwater often becomes dominated by filter-feeders, such as net-building caddisflies, that appear to ingest phytoplankton and zooplankton discharged from the project (Kondratieff and Voshell 1981). Species that feed on allochthonous material washed in from the watershed decline in numbers since much of this material will settle in the reservoir and not be available in the tailwater.

29. In an unregulated stream or river, the major sources of recruitment to a fish community are natural reproduction and instream movement. However, in a warmwater tailwater, natural reproduction of fish will be supplemented by passage of fish from the reservoir into the tailwater. Thus, the fish community in a tailwater downstream from a surface-release project may exhibit a shift in composition as reservoir fish recruit into the tailwater (Walburg et al. 1981). Additional sources of fish recruitment into the tailwater fishery may be of site-specific or seasonal importance. The discharge of forage fish from the reservoir may attract predatory fish into the tailwater. Fish may also concentrate in the tailwater because of blockage of upstream

spawning migrations and because release temperatures in winter may be warmer than water temperatures farther downstream.

Deep release on warmwater stream

30. The effects of deep release from thermally stratified reservoirs on warmwater streams and rivers are determined by the water quality at withdrawal depth and the extent of preimpoundment temperature alteration. The temperature effects and often the water quality alterations caused by deep release on formerly warmwater streams are usually extensive (Walburg et al. 1981, Walburg et al. 1983). Generally, mean and maximum temperatures are lowered in the tailwater, and the transport of particulate organic matter is disrupted. Although some warmwater organisms may be able to survive in the tailwater, they are unable to reproduce. Consequently, the abundances of many species of warmwater fishes may be reduced, and many common stream insect groups such as Ephemeroptera (mayflies), Trichoptera (caddisflies), and Plecoptera (stoneflies) are unable to colonize these areas. The benthic community is limited to species that do not appear to require a temperature stimulus for the normal progression of life-history stages (amphipods, isopods, oligochaetes, many coleoptera, and some dipterans). Low DO concentrations and high concentrations of reduced compounds, such as iron and manganese, in the discharges during periods of stratification in the reservoir may stress aquatic organisms in the tailwater and, in some systems, may account for the low diversity and biomass of tailwater biota in the summer and fall (Walburg et al. 1983). In some cases, iron and manganese precipitates may cover the substrate to the extent that macroinvertebrate and periphyton densities are reduced.

31. Deep-release projects in which the reservoir is stratified and the hypolimnion is anaerobic typically discharge clear, nutrient-rich water that fosters the growth of periphyton (Ward 1974, 1976, Gore 1977, Ross and Rushforth 1980); if the hypolimnion is aerobic, some phytoplankton, zooplankton, and fishes may be discharged into the tailwater. Deep releases into formerly warmwater streams may substantially alter the base of the food web in the tailwater. Rather than being based on allochthonous material such as leaves, bark, and detritus, the food web is based on periphyton, and the benthic community is dominated by grazers (organisms that scrape periphyton from rocks) and collectors (chironomids, oligochaetes, amphipods, and isopods) of detritus associated with periphyton. Dense periphyton growth can also act to obstruct or alter habitat for benthos and fish species (Gore 1977, Holmes and Whitton 1981, Dufford et al. 1987).

32. Species composition and fish abundance in the tailwater are partly determined by project operation. In tailwaters of deep-release flood-control (nonhydropower) projects that are drawn down extensively, the fish community may be dominated by fishes from the reservoir that appear to move through the reservoir outlet works into the tailwater or that seasonally concentrate below the dam during upstream migration (Jacobs et al. 1985). Tailwaters downstream from deep-release peaking hydropower projects are characterized by low biomass and diversity of fishes since fish passage through the outlet works is reduced and thermal and chemical conditions in the tailwater generally inhibit recruitment through natural reproduction.

33. Deep-release projects (particularly those with a relatively short hydraulic residence time) that support a put-and-take trout fishery on formerly warmwater streams may experience a shortage of cold hypolimnetic water during the late summer and early fall in some years. Thus, the trout fishery cannot be maintained throughout the year because increased water temperatures during the summer are detrimental to trout. Consequently, the tailwater environment becomes too warm for coldwater organisms and too cold for warmwater organisms since the coldwater temperatures earlier in the summer prevent natural reproduction by warmwater biota in the tailwater.

Deep releases on coldwater streams

34. The effects of deep release on a coldwater stream appear to be determined primarily by water quality, since the release temperatures generally fall within the tolerances of coldwater aquatic organisms, although in some instances release temperatures may be sufficiently cold to slow the growth rates of some organisms. However, Ward (1976) and others (see reviews in Ward and Stanford 1979, Petts 1984) have demonstrated that the phenomena of winter warm/summer cool tailwater conditions are sufficient to eliminate coldwater stream species which require thermal cues to complete their life cycles. Seasonal water quality problems may occur downstream from deep-release projects if the hypolimnion of the upstream reservoir becomes anaerobic.

Surface release on coldwater stream

35. The effects of surface releases warm enough to convert a formerly coldwater stream to a coolwater or warmwater stream are not well documented. There is some evidence that increased water temperatures in coldwater streams can favor warmwater organisms because the coldwater organisms may become less active as water temperatures increase (Walburg et al. 1981). As a result, the

growth rate of coldwater organisms may decrease, or the coldwater organisms may migrate out of the tailwater. Coldwater organisms may also become more susceptible to disease as water temperatures increase. In addition to these specific effects of warmwater release on coldwater organisms, other generalized effects are related to alterations in the yearly temperature cycle (delay in seasonal warming and cooling that can affect reproduction), alterations in the downstream transport of allochthonous material, and changes to preimpoundment water quality.

PART III: IMPACTS OF PEAKING HYDROPOWER OPERATION

Background

36. Part II described general impacts associated with reservoir projects. This section presents a suite of environmental impacts normally restricted to peaking hydropower operation including impacts of minimum flows, peaking flows, initial surge, and fluctuating flows.

37. Operation of a reservoir project for peaking hydropower production alters the preimpoundment riverine environment by changing both seasonal and daily flow patterns. Seasonal flow patterns are altered because seasonal high flows are at least partly retained for generation during low-inflow periods and also because reservoir projects authorized to generate peaking power usually have flood control as an authorized project purpose. Daily flow patterns are altered because releases are determined by daily demands for electrical power and not by short-term precipitation patterns within the basin. The extent of daily flow alteration is determined by the timing of demands for peaking power and the generation capacity (discharge) of the project relative to the channel capacity. Substantial daily fluctuations in water level can occur downstream as the project abruptly releases large amounts of water during generation following periods of reduced discharge. Increased discharges into the tailwater result in substantial increases in water depth and velocity over nongeneration periods. Stage differences of 5 m have been reported on the Cumberland River at sites immediately downstream of Wolf Creek Dam (Curtis, Nestler, and Martin 1987; Nestler et al., in preparation).

38. Peaking hydropower operation can result in more substantial downstream changes in physical habitat than nonhydropower operation. Not only is the downstream transport of sediment interrupted by the reservoir, but highly fluctuating flows may also increase bed scour, armoring, and bank sloughing and decrease stream gradient (caused by channel degradation near the project and increased sediment redeposition farther downstream). The extent of physical habitat modification (channel change) is determined by channel bed and riverbank composition and the velocity of the releases in the tailwater. Changes in physical habitat in the tailwater are most pronounced during the first several years of project operation. Over a period of years, the channel

approaches equilibrium and further changes become minor.

39. Peaking hydropower operation can alter downstream water quality. Water quality of hydropower releases is determined by chemical and physical conditions in the reservoir at the depth of withdrawal ar : changes occurring during passage of the water through the conduits, turbines, and stilling basin.

40. Significant short-term changes in water quality can occur in the tailwater if reservoir water quality at the depth of withdrawal is different from equilibrium conditions in the tailwater. These changes often occur after long periods of minimum release, when tailwater quality has been altered by insolation, photosynthesis, and other biogeochemical processes. The release of water from the reservoir into the tailwater will then cause rapid changes in water quality as the water in the tailwater is replaced by reservoir discharges (Figure 6).

41. The downstream extent of the reservoir's influence depends upon the difference between water quality at the depth of withdrawal and the equilibrium water quality of the river, the discharge rate, meteorological factors, and physical, chemical, and biological processes in the river such as oxidation, reaeration, respiration, and photosynthesis. Figure 7 illustrates some of the effects of peaking operation on the tailwater ecosystem. Note the consistent high densities of macroinvertebrates, chlorophyll-a, and POM during the initial surge associated with start-up of generation.

Impacts of Minimum Flows

42. Releases from peaking hydropower projects reflect demands for electricity. Minimum daily low flows are released when demand for peaking power is diminished, usually at night and early in the morning. Minimum weekly low flows occur on the weekend since demand for power is reduced on weekends. Minimum low-flow releases from a peaking hydropower project may be inadequate to meet the instream flow needs of tailwater biota.

43. Inadequate minimum flows from reservoirs are generally considered one of the most detrimental impacts of impoundment. Inadequate minimum low flows during nongeneration can stress tailwater aquatic biota in a number of ways. The carrying capacity of the aquatic habitat remaining in the tailwater may be substantially reduced as the wetted perimeter of the channel decreases

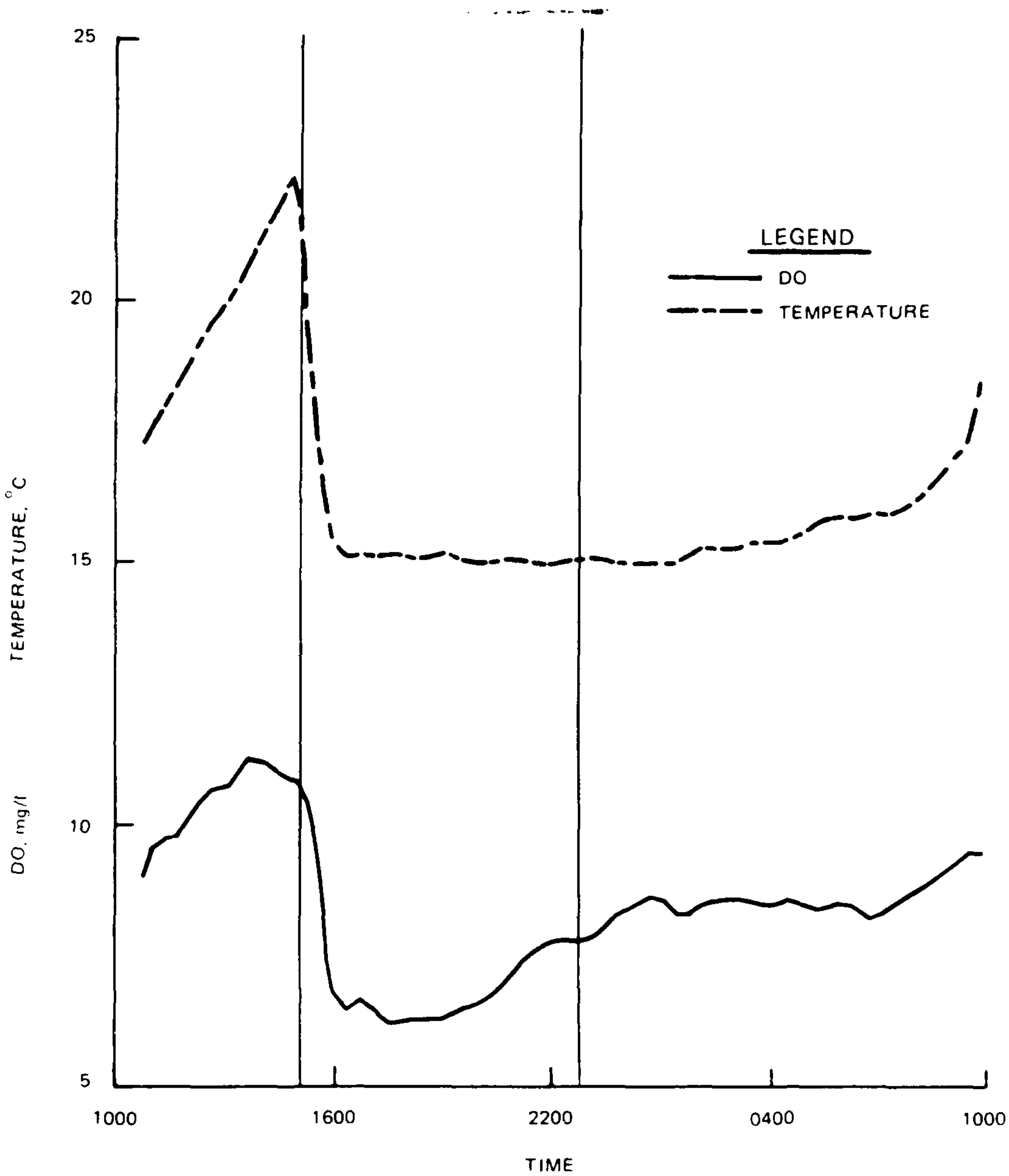


Figure 6. Changes in temperature and DO 4.5 km downstream of Lake Hartwell Dam during a July generation cycle. The vertical reference lines represent the passage of the initial surge (1500 hr) and the end of generation (2245 hr). Note the decrease in temperature and DO at the surge and the general recovery of these parameters after generation ceased (Nestler et al. 1986b)

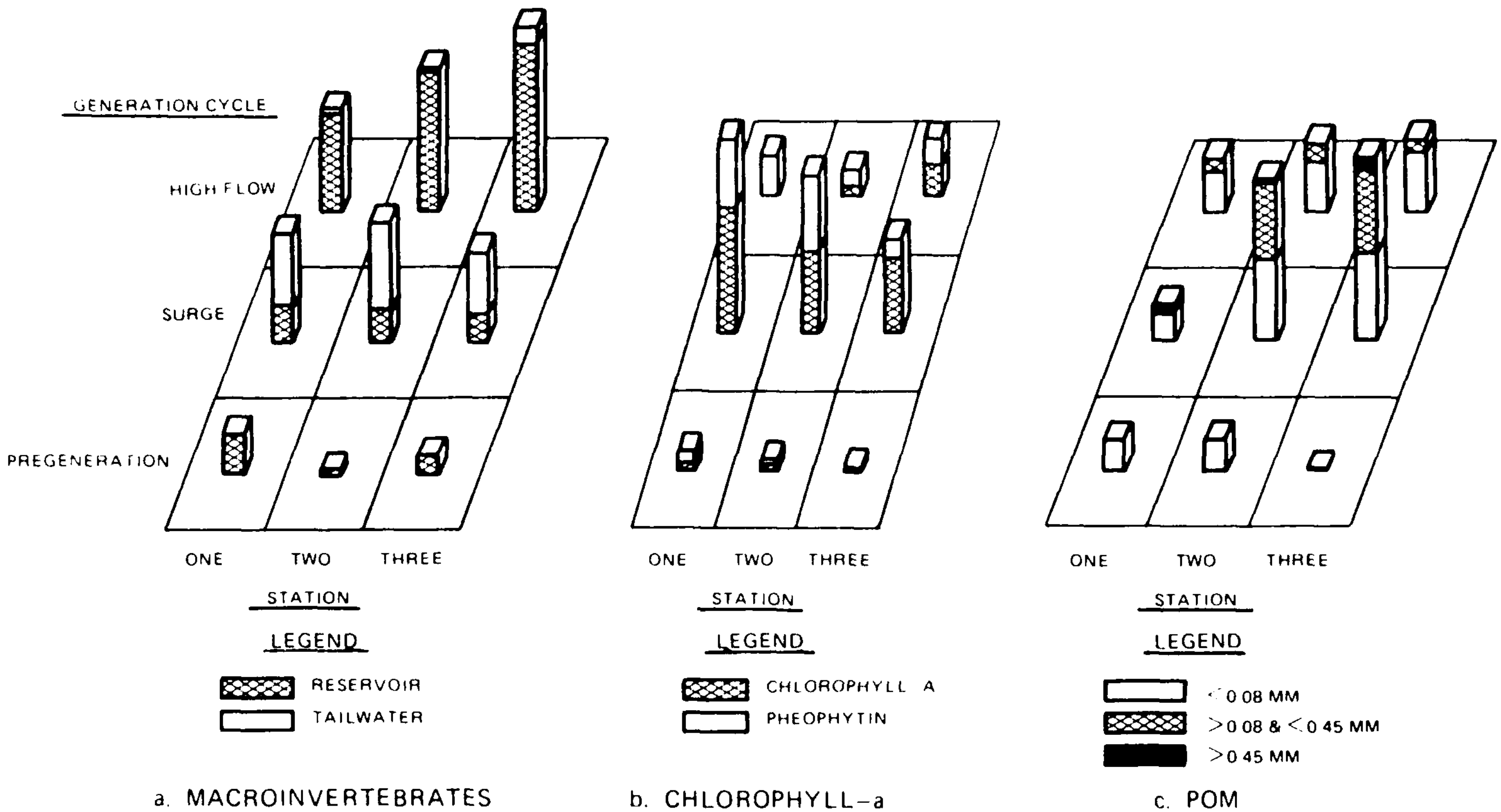


Figure 7. Estimated densities of macroinvertebrates (number m^{-3}), chlorophyll-a (mg m^{-3}), and POM (g AFDW m^{-3}) during a generation cycle downstream from a peaking hydropower project. Distances from the reservoir are as follows: Station 1--1.0 km, Station 2--4.0 km, and Station 3--12.1 km (Matter, Nestler, and Saul 1983)

with decreasing discharge. Riffle areas that produce much of the fish food in the river may dry out, leaving only a series of pools as refugia for aquatic organisms. Sessile organisms in riffles and shallows of tailwaters are desiccated, and mobile organisms are concentrated into remaining pools, resulting in increased competition for food and space. Predation within the pool increases both by aquatic organisms and by terrestrial and avian predators (raccoons, kingfishers, and herons). Reduced water velocities also decrease the density of drift and the food (fine POM) to filter-feeding invertebrates. Nesting sites of fishes may be dewatered with attendant mortality of eggs and fry. Also, in these pools, the effects of poor water quality may be intensified, particularly in the case of summer low flows when DO depletion, increased water temperature, and reduced stream reaeration may occur. In coldwater tailwaters, the effects of excessively warm water may be detrimental or lethal to coldwater fishes and invertebrates. Inadequate weekend minimum low flows have the potential to be deleterious, particularly over hot summer weekends when cold water released from a project can warm to near lethal levels over a 2-day period. Release of cold water on a following Monday may result in thermal shock to aquatic organisms in the tailwater. Inadequate winter low flows may subject aquatic biota to freezing, complete ice cover, anchor ice formation, and other harsh climatic conditions.

Impact of Peaking Flows

44. In unregulated streams, flows are determined primarily by precipitation patterns in the watershed. Flows range from very low (approaching zero in some cases) to flood flows that exceed channel capacity, with most flows at an intermediate level. In addition, the rate of change from one flow to another is usually very gradual in unregulated systems. Discharges from peaking hydropower projects differ considerably from unregulated systems because flows are concentrated near the minimum and generation discharges. The generation flows are less than the preimpoundment flood flows, although the generation flows occur much more frequently than natural high flows, often on a daily or weekly basis.

45. High flows associated with generation have been thought to disrupt the natural behavior of some aquatic organisms and result in a general degradation of habitat available for tailwater organisms. However, these

effects should, in many cases, be more correctly associated with either the effects of deep release, the extent of flow fluctuation (the difference between minimum and maximum flow) in the tailwater, inadequate minimum low flow, or the initial surge associated with generation. For example, density of entrained (swept up by currents) invertebrates is much greater during the surge period, when tailwater flow conditions change from low to generation flows, than during generation flows (Matter, Hudson, and Saul 1983; Matter, Nestler, and Saul 1983). Concomitantly, changes in physical habitat in the channel resulting from scour and armoring are caused not only by the generation flows, but also by the extent and rate of water-level fluctuations and the sediment-trap effect of the impoundment. Generation flows can result in some scour of benthic organisms and dislocation of fishes. However, generating flows usually do not cause significant catastrophic downstream movement of either fishes or invertebrates, especially if physical cover such as boulders, backwaters, and deep pools are available as refuges for tailwater fishes.

46. Generation flows can extend the downstream effects of poor release water quality. Generation flows carry water of poor quality farther downstream since the increased discharges result in both increased current velocity and a decrease in the surface:volume ratio of the flows, thereby reducing the rate at which the water quality of the releases reaches equilibrium with atmospheric and meteorological influences.

Impacts of the Initial Surge Associated with Start-Up

47. An initial surge of water is released into the tailwater during start-up of the turbines at a peaking hydropower project. Downstream environmental effects of the initial release surge are separate and distinct from the effects of sustained generating flows. The surge period is characterized by highly turbulent flows and rapid changes in depth, velocity, water temperature, and water quality. Although the initial surge associated with start-up usually lasts less than 30 min, it can potentially impact downstream aquatic biota both by increasing drift rates and by temperature shock as cold releases flow through a tailwater in which water temperatures had previously warmed to near equilibrium temperatures.

48. The effects of the initial surge are most pronounced near the reservoir. With time and distance, the amplitude of the generation surge is

dampened. However, the duration of the rising and falling limbs of the surge increases concurrently with the dampened peaking wave. That is, flows near the project are usually either low or high with a relatively short transition period occurring between generation and nongeneration. In contrast, flows farther downstream tend to be constantly rising and falling. Along the Cumberland River, for example, the rising limb of a generation surge will last 1 hr 1 km downstream of the dam while it will last 4 to 6 hr 40 km downstream (Nestler et al., in preparation). During this same surge, the stage difference between low and high flows will be approximately 5 m near the project but less than 1 m 40 km downstream. Although not completely investigated, the effects of two flow extremes connected by a brief surge period (as observed near the project) have a greater impact on aquatic biota than the gradually varying flows observed further downstream (Walburg et al. 1983).

49. In addition to downstream attenuation, the arrival of the surge is delayed as it moves downstream. For example, the peaking wave arrives 7.8 hr after generation begins 40 km downstream of Wolf Creek Dam on the Cumberland River. The delay in arrival of differing hydraulic conditions may affect the life cycles or survival of species that exhibit pronounced diel activity patterns (such as foraging and drift) (Gore, Nestler, and Layzer 1988). The downstream effects on biota of the delayed arrival of the surge as it moves downstream are probably not as severe as other impacts of peaking, such as temperature shock or inadequate low flows.

50. During start-up of the turbines at a peaking hydropower project, the initial discharge surge follows a period of minimum low flow that may have lasted from several hours (from one weekday to another) to several days (from Friday to Monday). The discharge surge during generation start-up substantially affects physical and chemical conditions in the tailwater. The physical effects are related primarily to the large flow gradients of the initial release. These large flow gradients may accelerate erosion, scour, and armoring in the channel. In addition, the surge may scour macrophytes, periphyton, and macroinvertebrates from the streambed. Additionally, the surge may disorient and entrain tailwater fish (Nestler et al. 1986a).

51. Start-up effects of generation on water quality are related to ambient meteorological conditions, the length of the nongeneration period preceding start-up, and water quality at the depth of release. Local meteorological conditions can substantially alter water quality of the releases

during long periods of nongeneration if the water quality at the depth of withdrawal is considerably different from equilibrium water quality. Water quality in the tailwater can change suddenly as generation releases flow through the tailwater. Extreme changes in water quality during the start-up may result in thermal and chemical shock to aquatic organisms.

Impacts of Fluctuating Flows

52. Discharges from a peaking hydropower project cycle between generation flows (up to and perhaps exceeding channel capacity) and nongeneration flows (as low as seepage). The difference between generation discharges and nongeneration discharges represent the extent of water-level fluctuation. Although the amplitude of hydropower water-level fluctuations may be equivalent to the amplitude of water-level fluctuations in an unregulated river, the frequency of major fluctuations, the rate of change of water levels, and the duration of a given water level in the tailwater are altered. Highly fluctuating flows may have a negative effect on tailwater biota.

53. "ighly fluctuating water levels can affect tailwater biota directly through frequent alterations in depth and velocity over short periods. The sudden changes in flow conditions may exceed the rate at which aquatic biota can adjust to new habitat conditions, resulting in either stranding at low flows or entrainment at high flows. Bain, Finn, and Booke (1988) found that over 90 percent of all fishes were found in areas characterized by shallow depths and low velocities along stream margins. They concluded that highly variable and unpredictable flow fluctuations reduce total fish community diversity. Elimination of some species and increased densities of other forms would appear to alter the energy dynamics of these communities as well. Highly fluctuating discharges that vary rapidly between seepage flows and channel-full flow intensify many of the deleterious effects of both minimum low flows, generation surge, and maximum generating flows.

54. Highly fluctuating water levels in the tailwaters of some peaking hydropower projects have biological impacts beyond those associated with minimum, maximum, and surge flows. Peaking hydropower projects can develop fluctuation zones (areas that are alternately dewatered and inundated during a generation cycle) in the tailwater that are unsuitable habitat for either terrestrial or aquatic organisms (only species of oligochaetes and chironomids

are apparently able to survive in the fluctuation zones). In many respects, the fluctuation zone may resemble the intertidal zone of some coastal areas. Many taxa of benthic insects, especially those considered quality fishfood such as mayflies, stoneflies, and caddisflies cannot maintain populations in the fluctuation zone. The production of these fishfood organisms is then lost from the system. Similarly, the fluctuation zone has a direct impact on fish recruitment. Shifts to more frequent peaking generation during spawning periods for kokanee salmon (*Onchorhynchus mnerka*) resulted in increased mortality of embryos from desiccation and low temperatures (Fraley and Decker-Hess 1987). This high incubation mortality was ultimately seen as poor or failed year classes. White and Wade (1980) reported transport of some whitefish eggs to areas of potential desiccation during dewatering but did not predict if the loss of these eggs would lead to overall failed or poor year classes. Gislason (1985) found increased densities of benthos with depth and a negative correlation to number of hours of dewatering during the prior 2 weeks. At corresponding depths, insect densities increased by 2 to 50 times under stable flow conditions.

55. Highly fluctuating water levels can also affect tailwater biota indirectly through long-term changes in channel geometry and substrate composition. These physical changes in the tailwater associated with fluctuating water levels may result in substantial habitat alterations. Changes in physical habitat are contingent upon the degree of erosion (and consequent channel degradation), bank sloughing, sediment redistribution, and channel widening. For example, Gore and Pennington (1988) suggest that reduction in chironomid densities in immediate tailwaters is due to elimination of deposited fines that were redeposited farther downstream.

56. The severity of bank sloughing for a given tailwater is dependent upon the frequency and amplitude of water-level fluctuations. Pore-water pressure is directly related to the difference between the water table in the bank and the water level in the tailwater at low flow. Thus, large fluctuations in water level that often accompany peaking hydropower operations are especially conducive to bank sloughing as the streamflow varies from near-zero (dry channel) to channel capacity and back to zero in a matter of a few hours. Although unregulated streams may fluctuate in water level over similar ranges in response to stormflow, these natural fluctuations in water level are

neither as frequent nor as rapid as may occur below dams operated to meet peak power demands.

57. The net effects of fluctuating water levels on the tailwater channel near the project are to increase erosion, bank sloughing, armoring, and channel width and to decrease channel gradient. Farther downstream as peak discharges associated with generation decrease and the amplitude of water-level fluctuation attenuates, the net effect of fluctuating water levels is to increase sedimentation rates, as the sediment eroded near the project is redeposited downstream. All of these processes may result in substantial alterations in the location and quality of the physical habitat available to the tailwater biota.

PART IV: PREDICTING HABITAT AVAILABILITY

Instream Flow Incremental Methodology

58. Relating hydropower operation to downstream impact on aquatic habitat is complicated by the complex nature of peaking generation. The duration of generation may vary considerably depending upon the demand for power and the availability of storage water. The quantity of releases varies depending upon the number of turbines used for generation. Consequently, the hydraulic environment downstream of peaking hydropower projects exhibits substantial spatial and temporal variation. Most methods lack sufficient hydraulic detail to assess the downstream effects of peaking hydropower operation.

59. The IFIM (Bovee 1982) combines measured or predicted hydraulic parameters (usually depth, velocity, and cover or substrate) with habitat preference criteria in PHABSIM to predict changes in available habitat associated with different water resources development alternatives. The IFIM procedure is a combination of hydraulic models frequently used by engineers and biological models of habitat use or preference. The use of simple hydraulic models in the methodology facilitates its application for assessing impacts of peaking hydropower operation.

60. The IFIM is most commonly used to assess the effects of change from one steady flow to another. Common example applications include assessing the effects of streamflow diversion for irrigation or water supply. Use of IFIM as an aid for estimating minimum instream flow requirements has gained wide acceptance (Stalnaker 1982); however, the application of the same procedure to dynamic flows (as in peaking generation) is still in its infancy.

61. Recently, a few studies have attempted to predict effects of peaking operation on habitat availability. Using the dynamic flow model RIV1 (Bedford, Sykes, and Libicki 1983) linked to PHABSIM, Curtis, Nestler, and Martin (1987) assessed gains or losses in habitat for adult rainbow trout and adult and juvenile brown trout in the Cumberland River downstream of Wolf Creek Dam, from the dam structure to a region of a proposed reregulation dam. In a similar study, Nestler et al. (in preparation) employed the dynamic flow model BIRM (Johnson 1983) to provide predictions of trout habitat gain or loss in the Cumberland River from Wolf Creek Dam to Burkesville, KY, 37 miles

(59 km) downstream under conditions of present generation and proposed turbine uprate schedules. In both Cumberland River studies, declines in available trout habitat were predicted during periods of peaking releases. Although relative losses declined with distance from the dam, some habitat losses persisted at points over 40 km from the dam. Similar results were obtained by Bovee (1985). Using habitat suitability criteria developed by Gore and Judy (1981), he predicted habitat availability for the mayfly, *Rhithrogena hageni*, and the net-spinning caddisfly, *Cheumatopsyche* sp., under peaking hydropower operation. Bovee reported up to 75-percent habitat losses under greatest peaking releases.

Case Study: Caney Fork River

Background

62. The research was conducted in the tailwater of Centerhill Dam on the Caney Fork River in Tennessee. The Caney Fork River is typical of a deep-release peaking hydropower project on a formerly warm tailwater ecosystem. In addition, Center Hill Dam, along with other dams in the Cumberland River drainage, is under examination by the US Army Engineer District, Nashville, (ORN) for possible turbine uprate.

63. The Caney Fork River, a tributary of the Cumberland River, has its headwaters in central Tennessee. The ORN regulates flows at Center Hill Dam to provide for peaking hydropower production, flood control, and other project benefits. Center Hill Dam, located in DeKalb County, Tennessee, is an earthfill structure with a concrete overflow portion. The lake has a storage capacity of 2.58 billion cubic metres with an average surface area of 9,332 ha. The dam structure has a maximum height of 76.2 m and a length of 658 m. The powerhouse contains three turbines, each with a capacity of 45,000 kW/hr. Gordon (1979) reported annual spring stratification and fall turnovers. During stratification, DO depletion in the metalimnion and hypolimnion has been observed as well as increased phosphorous and nitrogen concentrations in the hypolimnion.

64. The Caney Fork River downstream of Center Hill Dam currently supports a valuable "put-and-take" trout fishery. The Tennessee Wildlife Resources Agency regularly stocks the river with rainbow trout (*Salmo gairdneri*) and has recently begun to stock brown trout (*Salmo trutta*). Other

tailwater sport fishes include small populations of smallmouth bass (*Micropterus dolomeui*, walleye (*Stizostedion vitreum*), and channel catfish (*Ictalurus punctatus*). Forage species in the Caney Fork include the gizzard shad (*Dorosoma cepedianum*), threadfin shad (*Dorosoma petenense*), and the banded sculpin (*Cottus carolinae*). Sculpins have been reported as a diet item of trout in other rivers, although this does not seem to be the case for the Caney Fork trout (Odenkirk 1987). Sculpins are a significant component of the benthic community and have been shown to be major regulators of macroinvertebrate densities and community dynamics (Flecker 1984, Hershey and Dodson 1985, and Anderson et al. 1986) as well as hosts for mussel glochidia (Zale and Neves 1982). The diet of trout varies temporally in the Caney Fork, with fall and winter diets dominated by drifting and benthic invertebrates. Spring diets include significant numbers of gizzard shad, which are probably passed through the turbines from the reservoir. Summer diets are dominated by terrestrial insects that fall into the water or are entrained by rising water levels during peaking generation.

65. Generation schedules vary with demand and season. Most often, generation is with one or two turbine units for periods of 6 to 12 hr (Figure 8). However, there are periods of full generation of up to 2 weeks to adjust lake levels. Attenuation of stage and increase in duration of the rising and falling limbs of the peaking surge were observed at stage recorders provided by ORN (Figure 9). The delay in arrival of the peaking wave to the most downstream experimental site (20 km from Center Hill Dam) was approximately 3 hr.

Survey techniques

66. The Caney Fork River has well-defined zones of degradation, aggradation, and recovery. A sampling station was established in each of these zones (Figure 10). Station 1 represents a degraded (in terms of sediment distributions) river reach typical of peaking hydropower operation. Station 2 represents an aggraded river reach in which the sediment scoured from near the dam is redeposited. Station 3 is representative of the channel prior to impoundment. Station spacing allows comparison of habitat conditions under variable hydraulic conditions as the peaking surge attenuates in its passage through the system.

67. Assessments of flow impacts were based on detailed mapping of habitat features and multiple hydraulic calibrations at each station. A

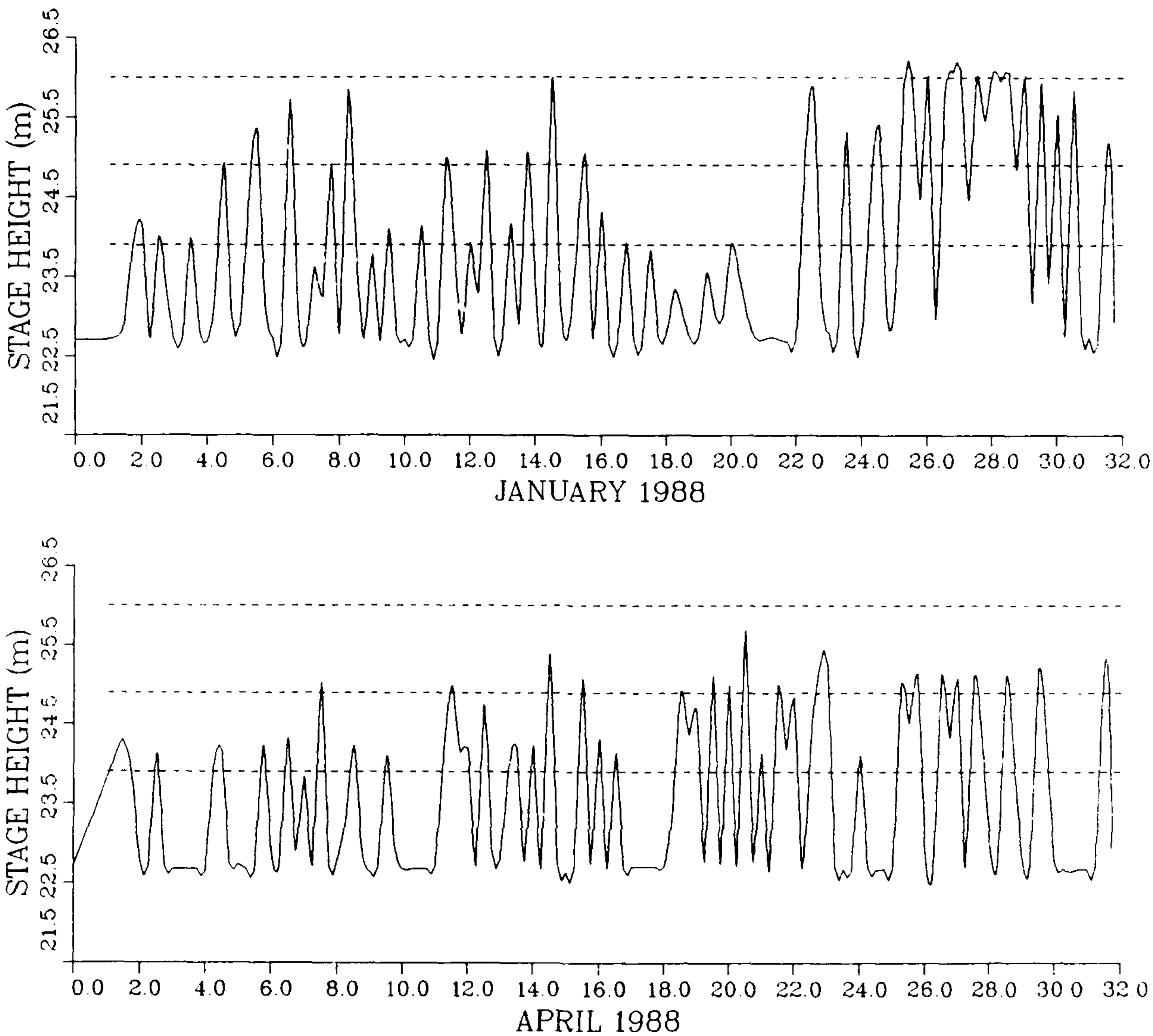


Figure 8. Stage record of Caney Fork River at Station 1 for January and April 1988. Dotted lines represent stage heights measured for one turbine (lower line), two turbines (middle line), and three turbines (upper line) in operation

series of permanent transects were established by surveying permanent tag line headpins to a common datum at each site. Transects were placed across major hydraulic breaks during maximum generation. Each transect was as close as possible to perpendicular to the major direction of the flow while maintaining the same water surface elevation across the transect. Additional transects were added at some sites at points of hydraulic change during low-flow periods. The total length of each surveyed sample site was about 500 to 700 m. Transect intervals varied but averaged about 60 m. At intervals of

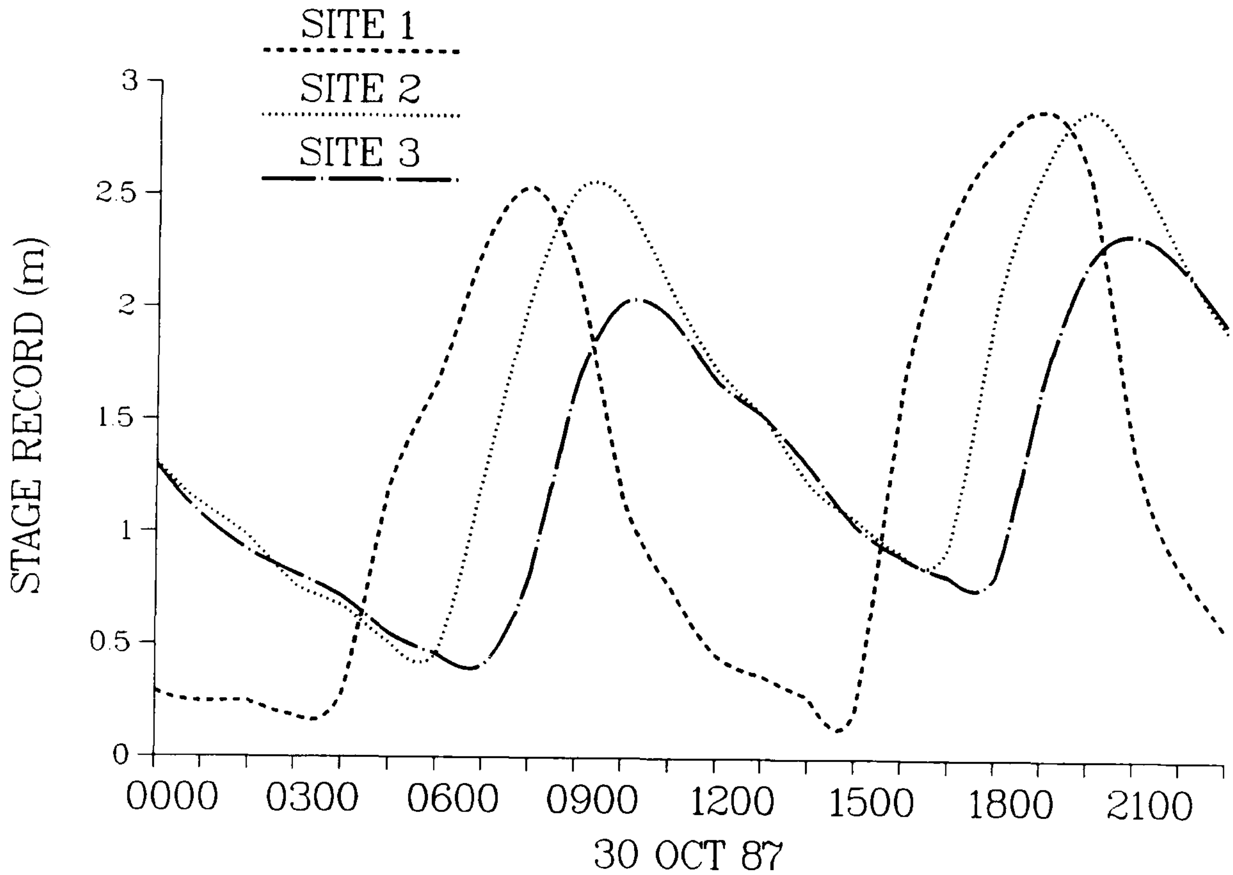


Figure 9. Stage record for 24-hr period during generation at all three sample sites. The peak centered at approximately 0800 hr represents the stage change from minimum flow to two-turbine generation. The peak centered at approximately 1900 hr represents the stage change from minimum flow to three-turbine operation

3.05 m along each transect, measurements of depth, velocity, and substrate character were recorded. Velocity measurements were recorded with a Price AA current meter, suspended from a 14-ft (4.26 m) johnboat attached to the tag line or with the current meter (Price AA or Marsh-McBirney) attached to a wading rod in shallow areas. When depths were over 60 cm, measurements of velocity were taken at 0.2, 0.8, and 0.9 × depth to calculate the best estimate for mean water column velocity as well as subsequent development of velocity profiles for nose velocities and near-bottom hydraulic conditions. At depths less than 60 cm, mean water column velocity was recorded at 0.6 × depth. Substrate/cover value was recorded in two fashions. First, a linear channel index (Nestler et al. 1986b) was recorded for each site (Table 1). Substrate values were also recorded on a modified scale of particle dominance and general cover value (Table 2).

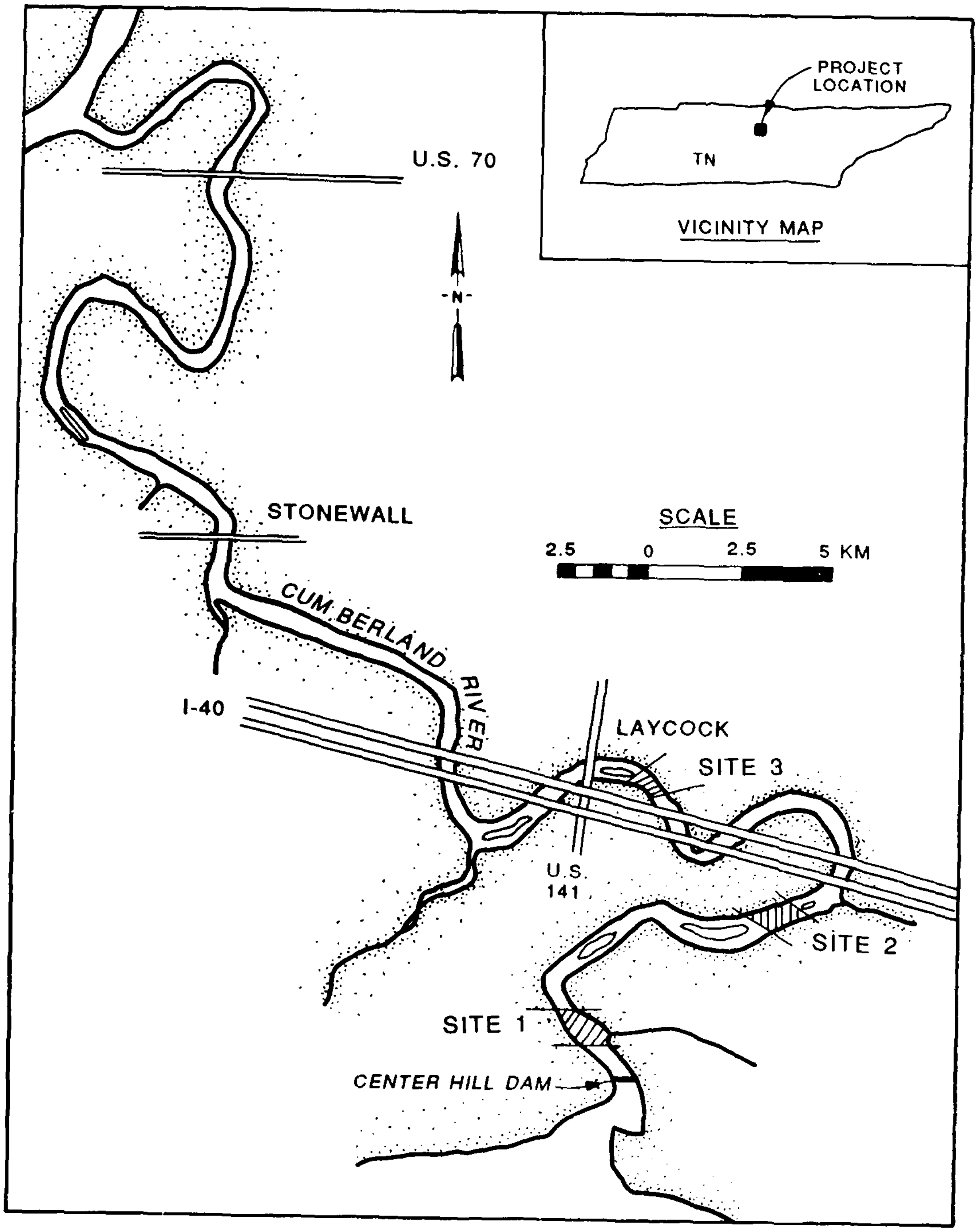


Figure 10. Sampling stations on the Caney Fork River

Table 1

Channel Index Used on the Caney Fork River

Index	Description
1.0	All sand--no cover
1.5	Gravel--no cover
2.5	Sand--some cover
3.0	Sand--extensive cover
4.0	Gravel--extensive cover
5.0	Cobble (75 to 254 mm)--some cover
6.0	Boulder--some cover
7.0	Bedrock--some cover
8.0	Cobble--extensive cover
9.0	Bedrock--extensive cover
10.0	Boulder--extensive cover
11.0	Upland vegetation

Table 2

Substrate Code Based on Particle Dominance and Cover Value*

Substrate	Cover	Vegetation
1 = fines	.1 = no cover	.01 = none
2 = sand	.2 = some cobble	.02 = <25% logs
3 = gravel	.3 = extensive cobble	.03 = 25-50% logs
4 = cobble	.4 = some boulders	.04 = 50-75% logs
5 = boulders	.5 = extensive boulders	.05 = >75% logs
6 = bedrock	.6 = bedrock	.06 = <25% upland veg.
		.07 = 25-50% upland veg.
		.08 = 50-75% upland veg.
		.09 = >75% upland veg.

* Code value is the sum of substrate + cover + vegetation scores based on qualitative observations.

68. Measurements at each transect were taken at low flows (no generation) (5 April 1987-11 April 1987) and full generation (three turbines) (10 March 1987-13 March 1987) at Station 1. Measurements at each transect were taken at low flows for Station 2 (24 April 1987-2 May 1987) and Station 3 (3 May 1987 and 23 July 1987) and selected transects at partial generation (one unit) at both Stations 2 and 3 (19 July 1988).

69. Flow information was used to generate habitat maps of the study sites at various flows as well as to calibrate the IFG-4 portion of PHABSIM. Using the IFG-4 program, it was possible to predict flow conditions throughout each site under different stages at a high level of resolution.

Site 1

70. Description. This site exhibits many of the characteristics associated with peaking hydropower operation. The channel is degraded and armored because peaking flows have removed many of the finer sediments and have left behind a substrate layer characterized by large and medium cobble (Figure 11). The thalweg of the stream runs fairly straight through this section and crosses to the opposite bank at the most downstream areas measured (Figure 12). As can be seen by comparing substrate and bathymetry plots, a substantial gravel/cobble bar is exposed at low flows (Figures 13 and 14) and inundated at high flows (Figure 15). During low flows, maximum velocities reach 45 cm/sec at riffle areas in the downstream end. However, during

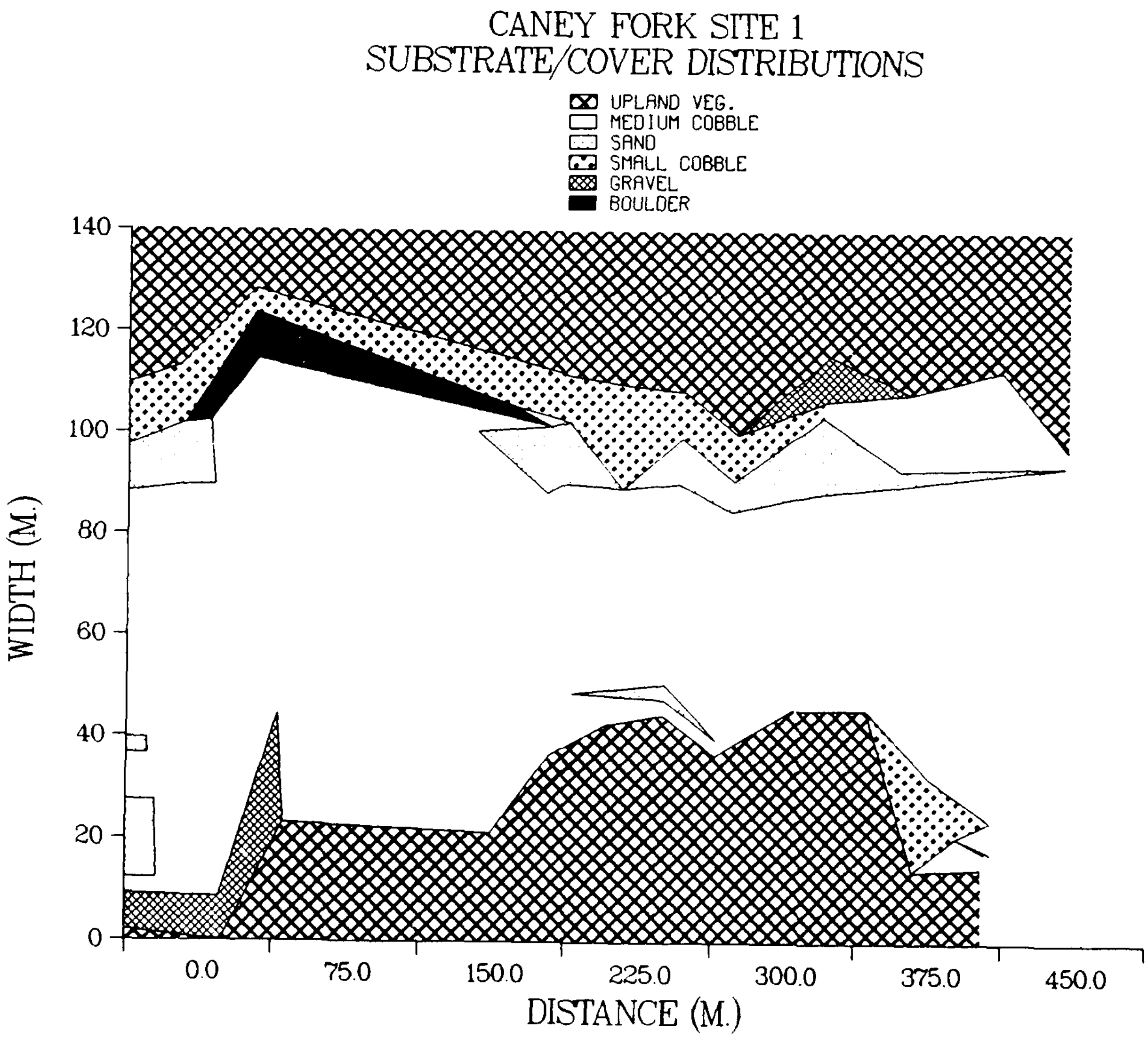


Figure 11. Site 1 substrate distributions on the Caney Fork River

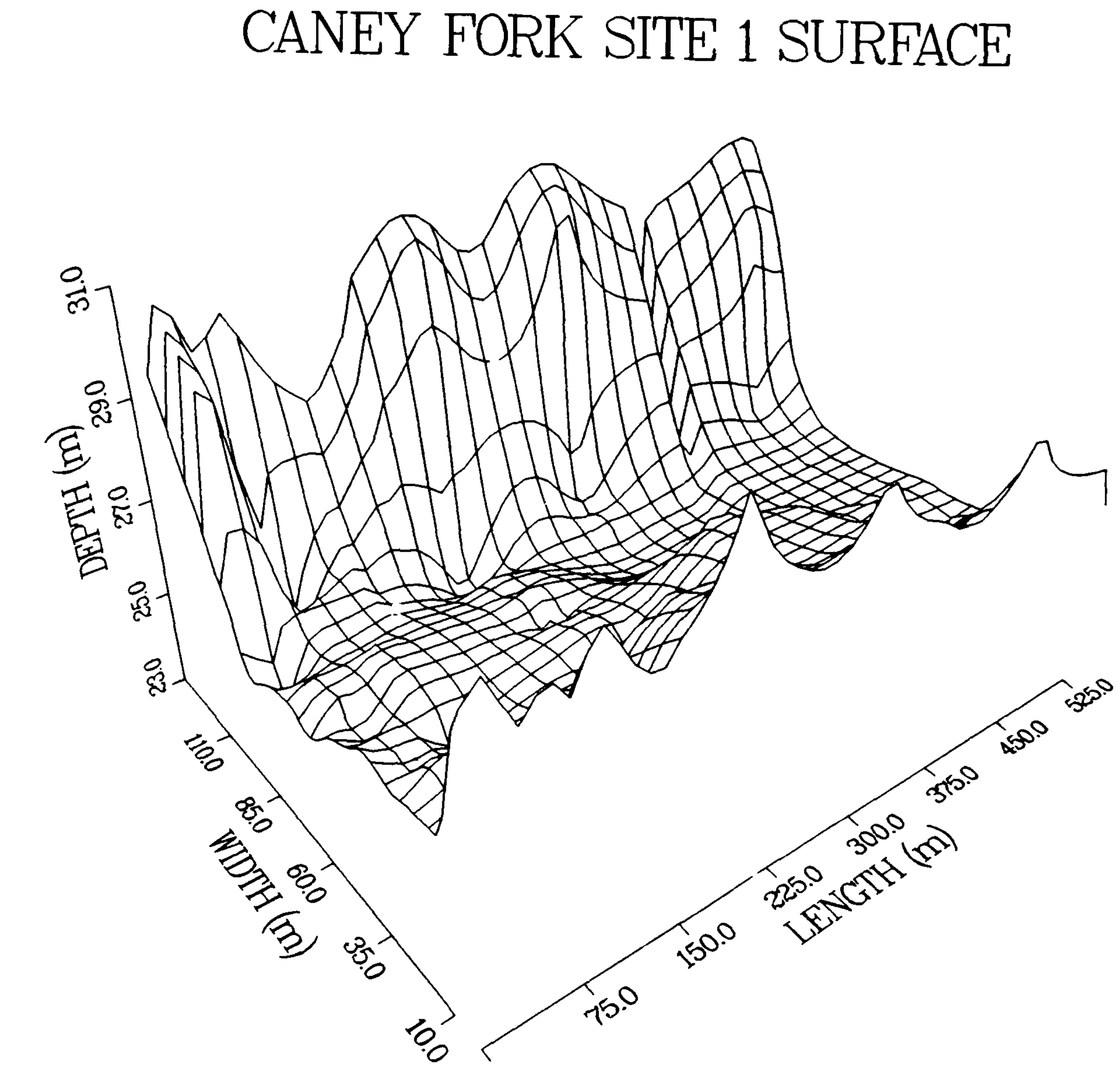


Figure 12. Site 1 bathymetry plot

low-flow periods, the majority of the flow is at velocities of less than 10 cm/sec with depths less than 60 cm (Figure 16). During high-flow, velocity distributions in the main channel (as opposed to overbank areas) remain homogeneous with well over 50 percent of the velocities exceeding 100 cm/sec (Figure 17). The majority of the lowest flows (<30 cm/sec) occur in the overbank areas of flooded upland vegetation. Depth distributions during full generation are quite homogeneous with over 80 percent of the depths falling between 2.8 and 3.8 m and virtually no shallow areas (<1 m) found at this site.

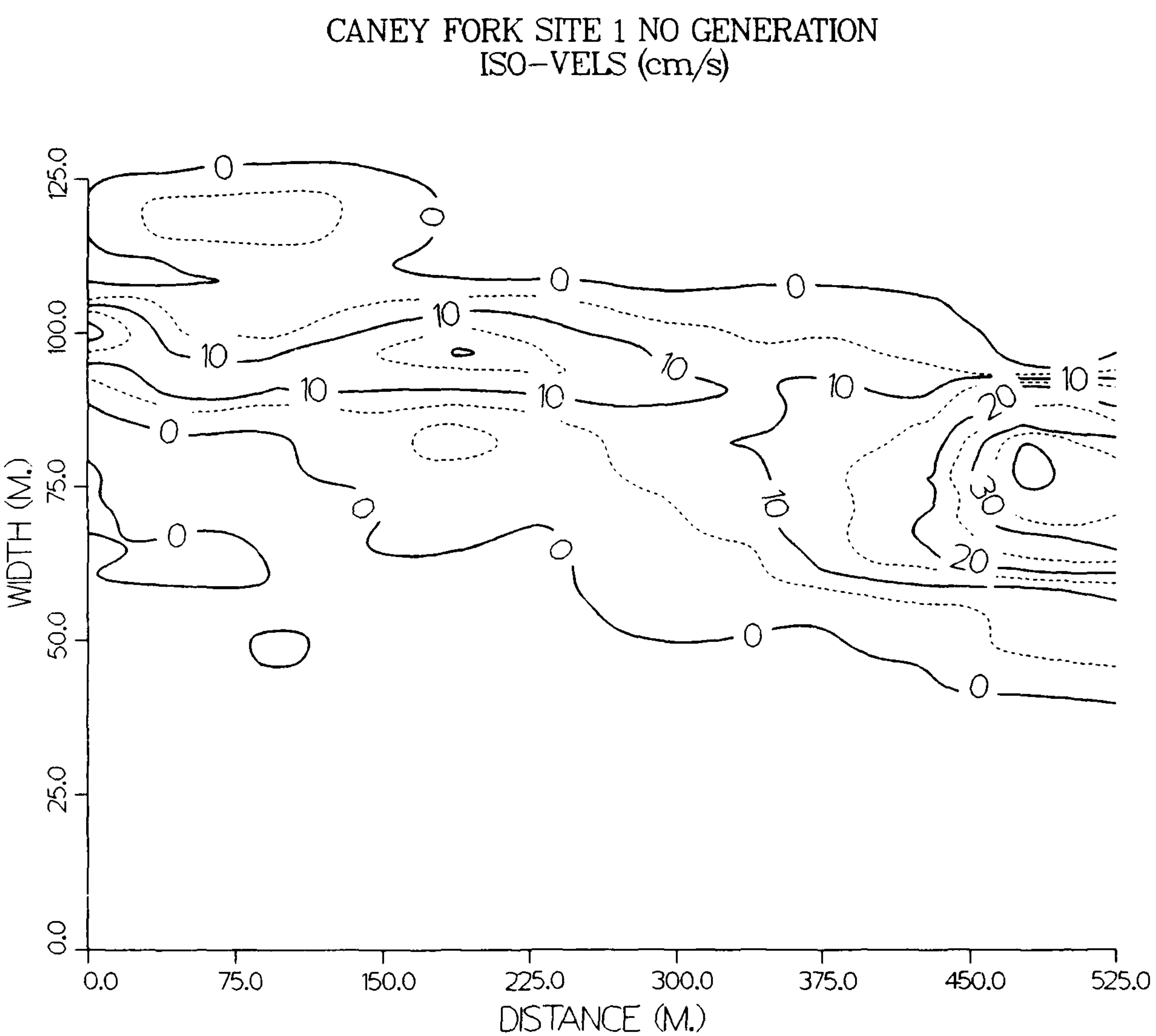


Figure 13. Site 1 flow pattern (isovels in 5-cm/sec intervals) during nongeneration flows

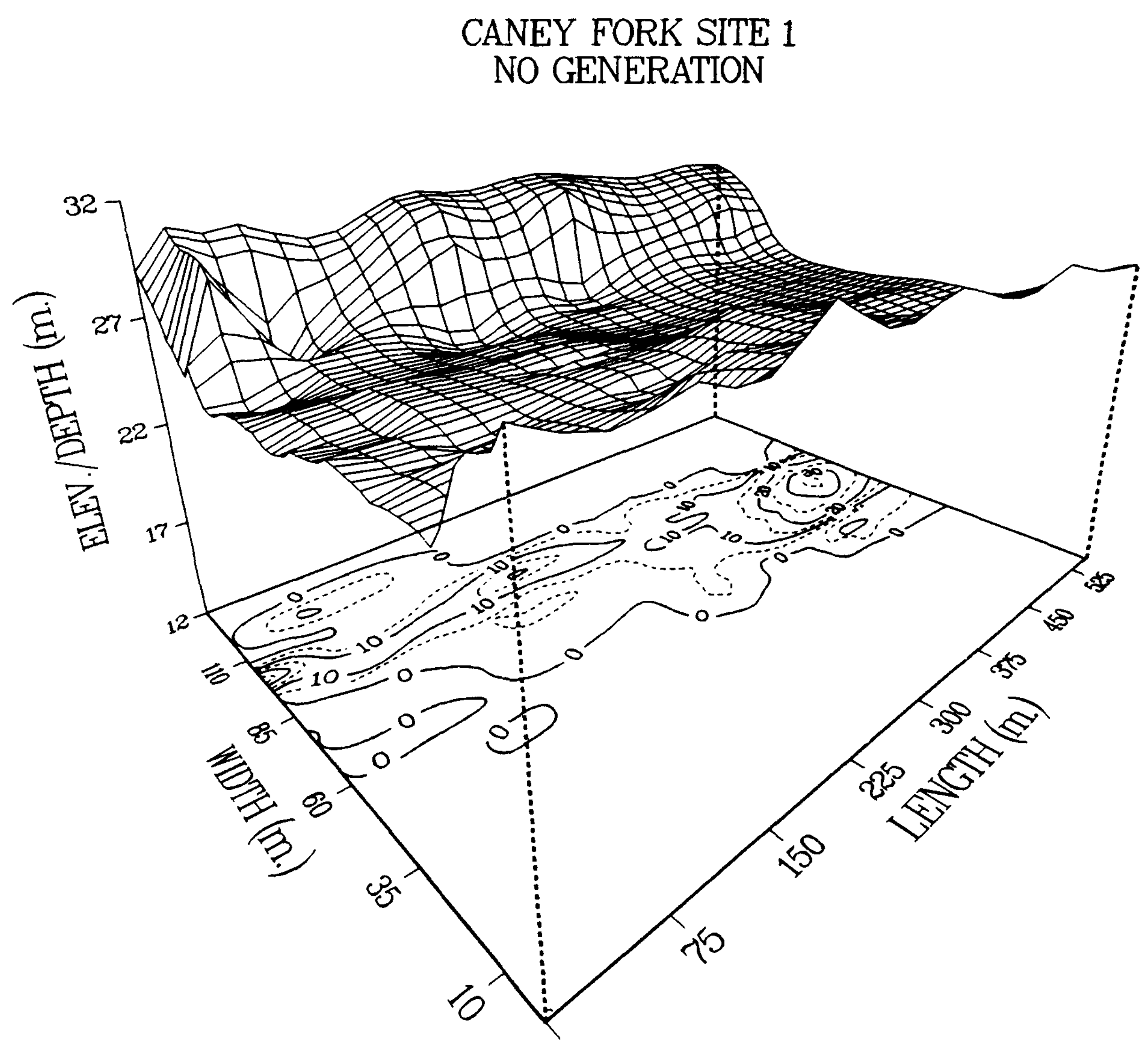


Figure 14. Combined view of channel bathymetry and velocity distributions (5-cm/sec isovel increments) for Site 1 during nongeneration

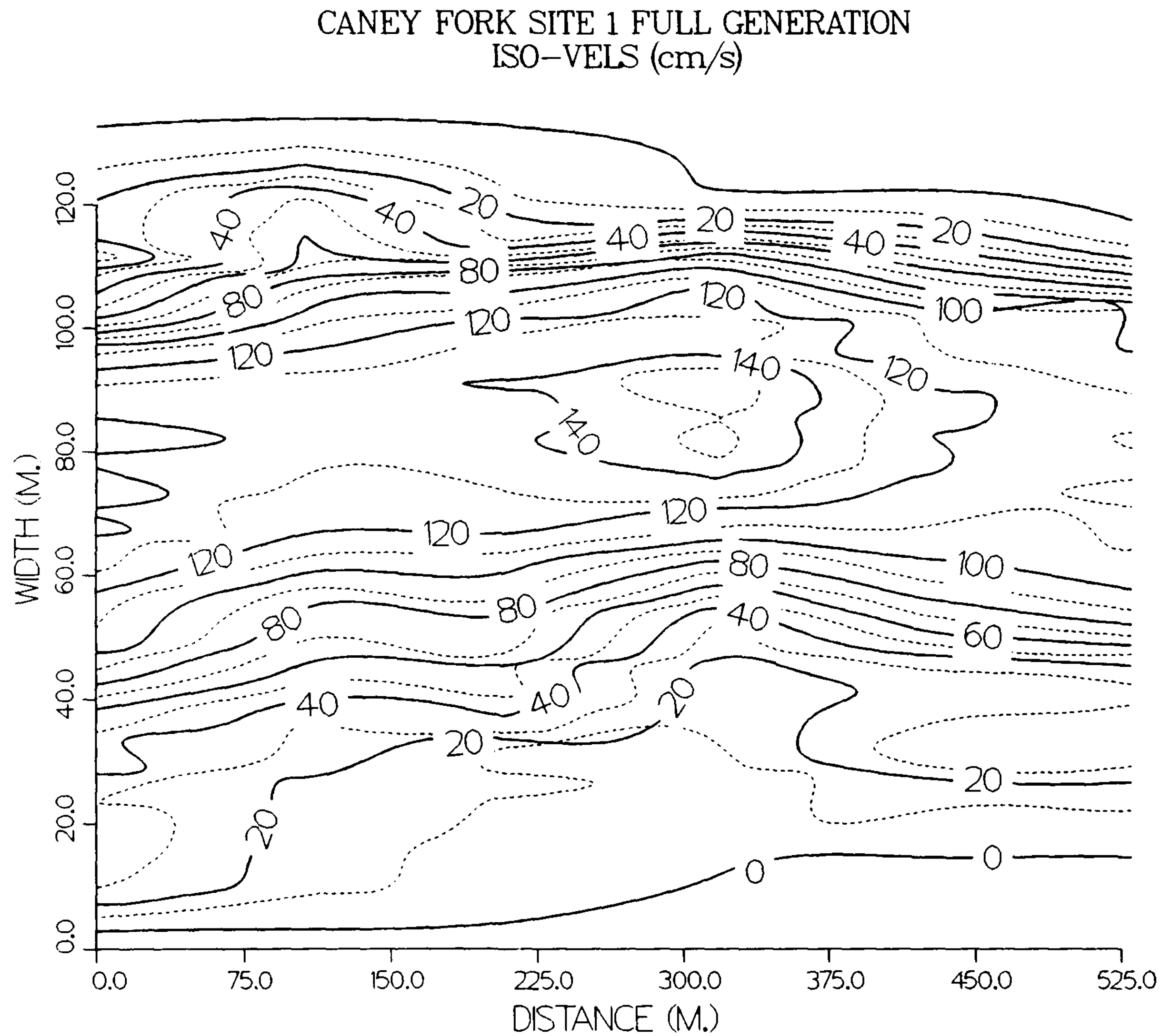


Figure 15. Full (three turbine) generation flow pattern (isovels in 10-cm/sec intervals) at Site 1

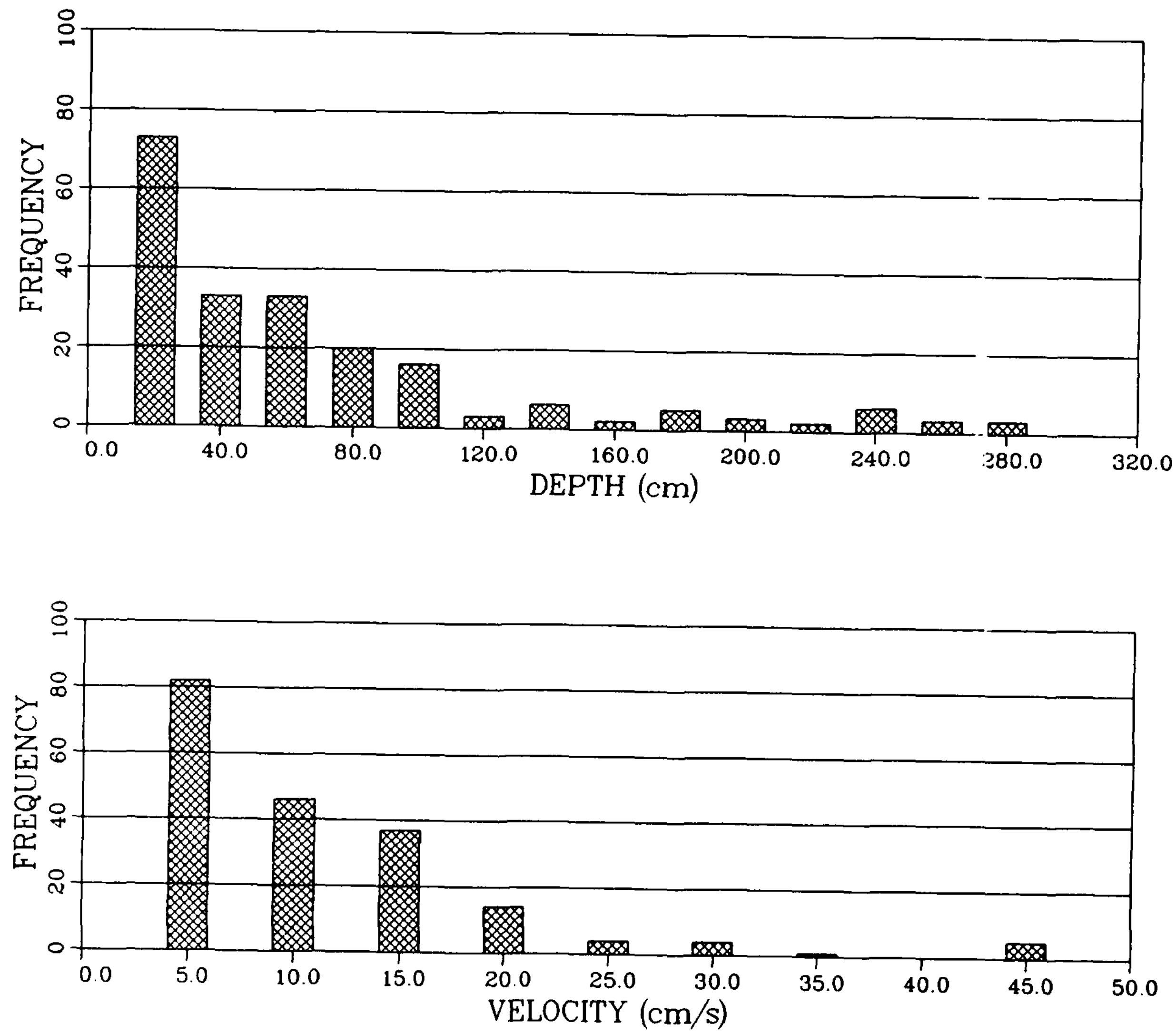


Figure 16. Frequency distribution of depth (increments of 20 cm) and velocity (increments of 5 cm) at Site 1 during nongeneration

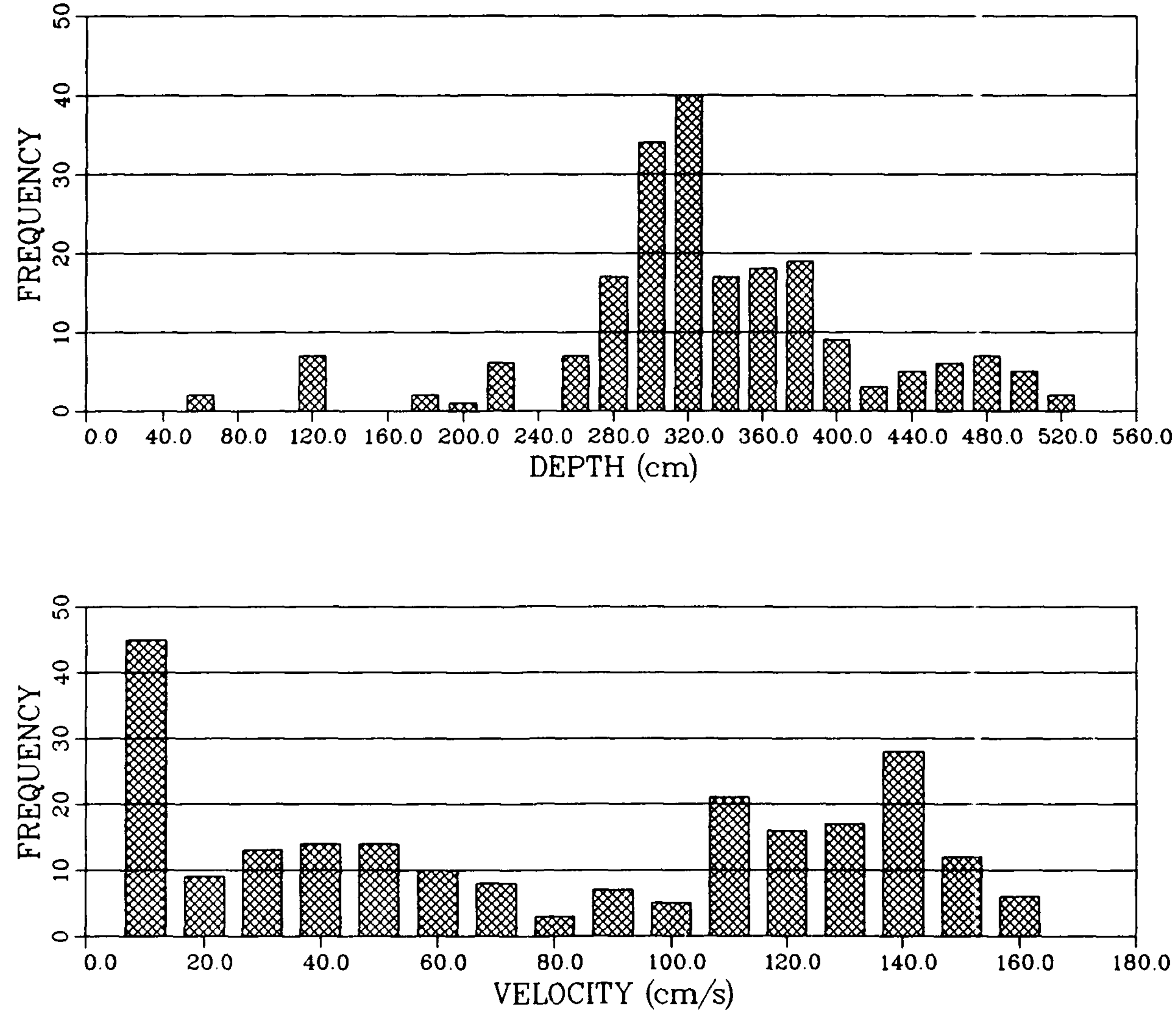


Figure 17. Frequency distribution of depth (increments of 20 cm) and velocity (increments of 10 cm/sec at Site 1 during full generation

71. Discussion and analysis. Statzner and Higler (1985) and Statzner, Gore, and Resh (in press) predicted that highest diversities of biota should occur in areas where the heterogeneity of hydraulic habitats is also highest. At first glance, it would appear that low-flow conditions were relatively homogeneous while high-flow periods were more heterogeneous. However, during high flows, the majority of moderate velocities and shallow depths occurred over areas dewatered at low-flow periods. Consequently, hydraulic conditions in those parts of the channel covered throughout the generation cycle are either shallow with low velocities or deep with high velocities. Moderate flow/shallow depth areas are probably unavailable to nonmobile species like benthic macroinvertebrates.

72. Shear stress has been identified (Statzner, Gore, and Resh (in press)) to be a major factor controlling the distribution of aquatic biota in streams. Statzner, Gore, and Resh (in press) have demonstrated that a wide suite of organisms are adapted to utilize certain shear conditions on and within the substrate. They have reduced survivorship at conditions other than those to which they are adapted (see also discussions by Schwoerbel 1967). Extreme changes in shear stress conditions across the bottom of the channel between generation and nongeneration at this site probably limit aquatic biota.

Site 2

73. Description. This site, located about 8 km downstream of Center Hill Dam, is in a zone of sediment aggradation. Material eroded from the banks and substrate upstream have been redeposited here. The predominant substrate is gravel and sand (Figure 18) rather than the medium and large cobble found at Site 1 and over most of the Caney Fork River. Increased sediment deposition has produced a broad channel with extensive stream braiding. Many islands are exposed during low flows (Figures 19 and 20). Velocities and depths at this site during low flow vary considerably (Figure 21), and the thalweg is difficult to define.

74. At simulated full generation, water flows across the entire width of the sample area (Figure 22). At high flows, hydraulic conditions are varied with highest velocities reaching 190-cm/sec and depths up to 4 m (Figure 23). At low flows, most velocities are less than 40 cm/sec, and the majority of depths are between 2 and 3.4 m. As at Site 1, moderate flows occur primarily over areas that were dewatered during nongeneration periods.

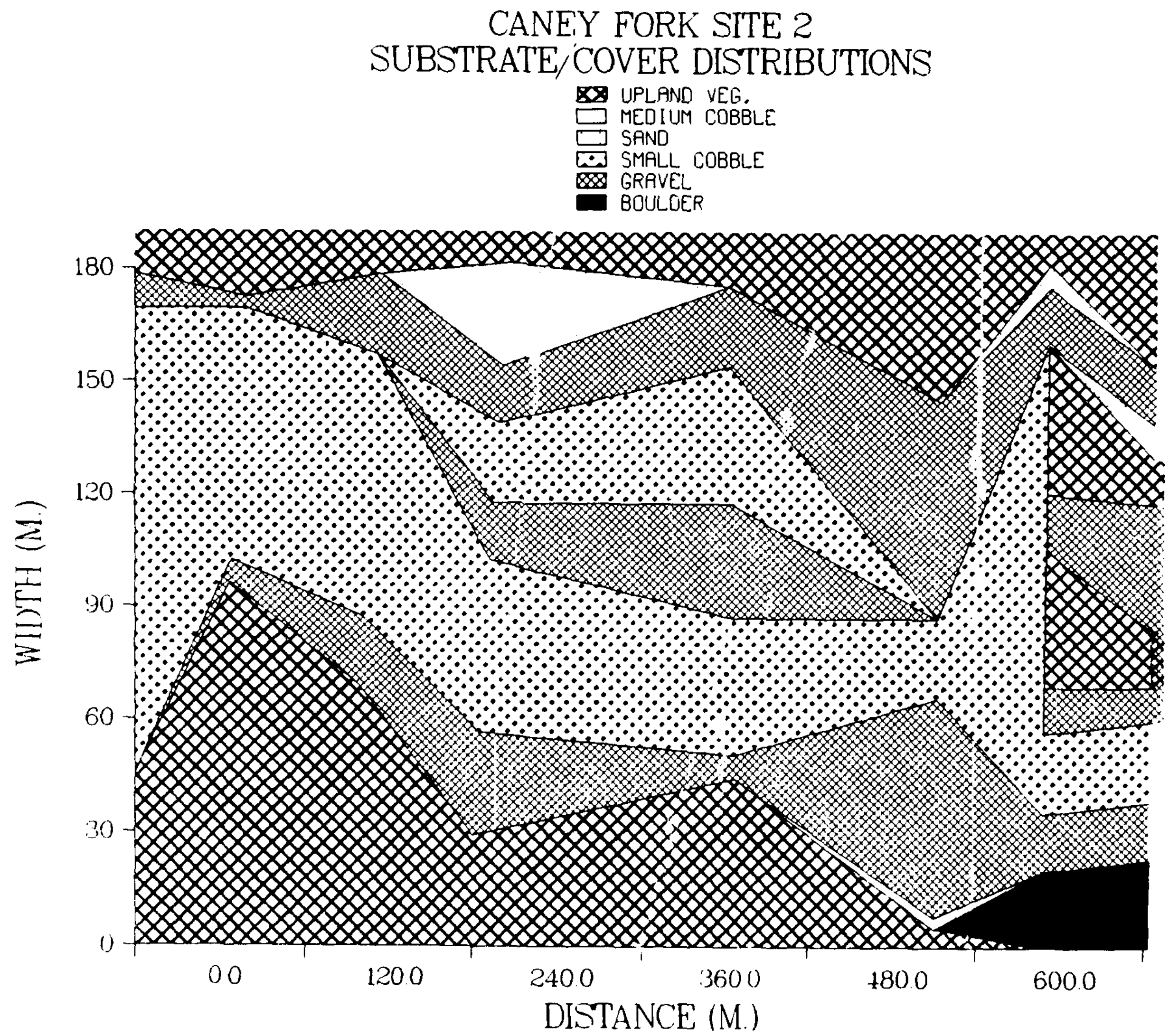


Figure 18. Site 2 substrate distribution

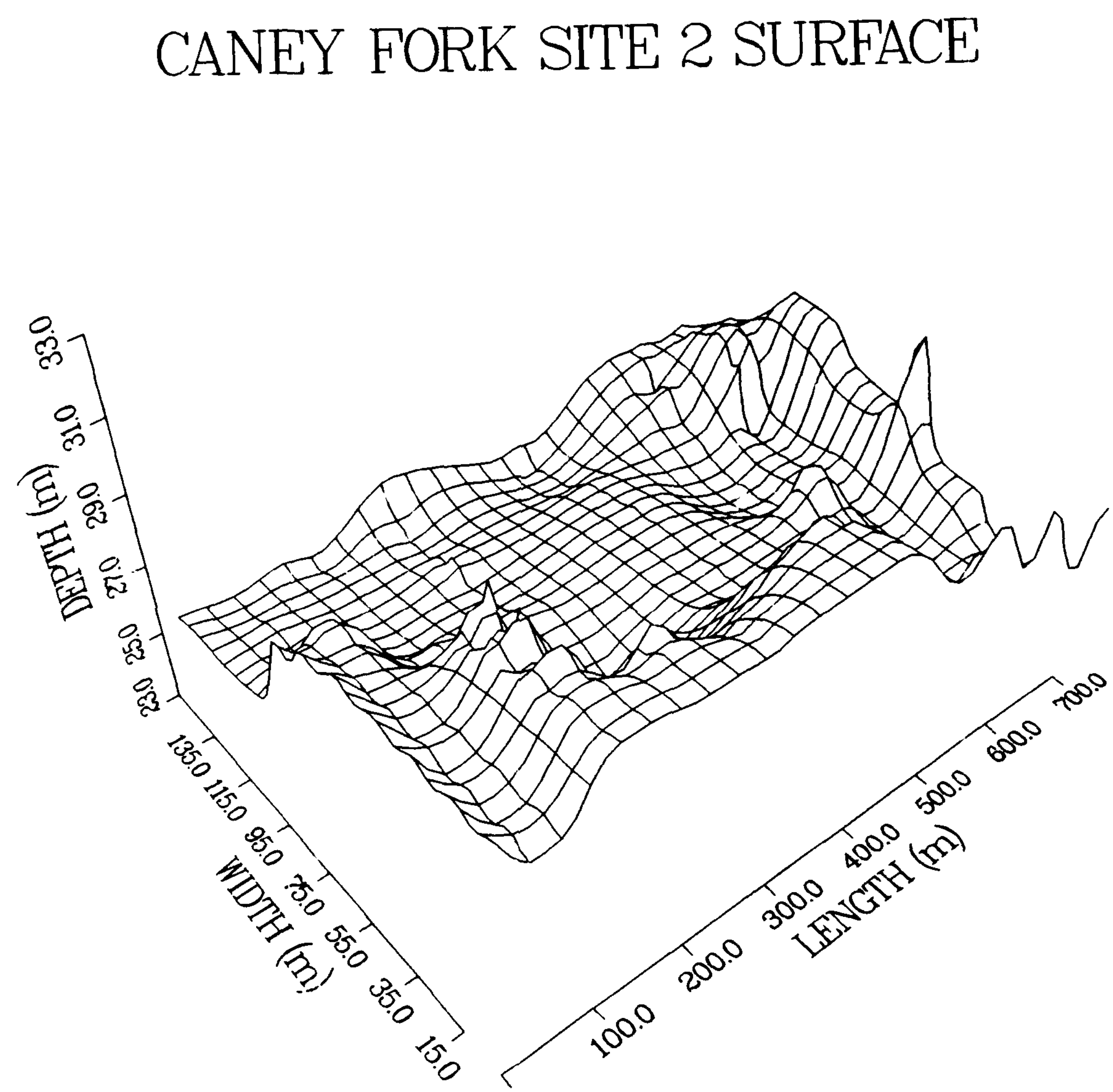


Figure 19. Site 2 bathymetry

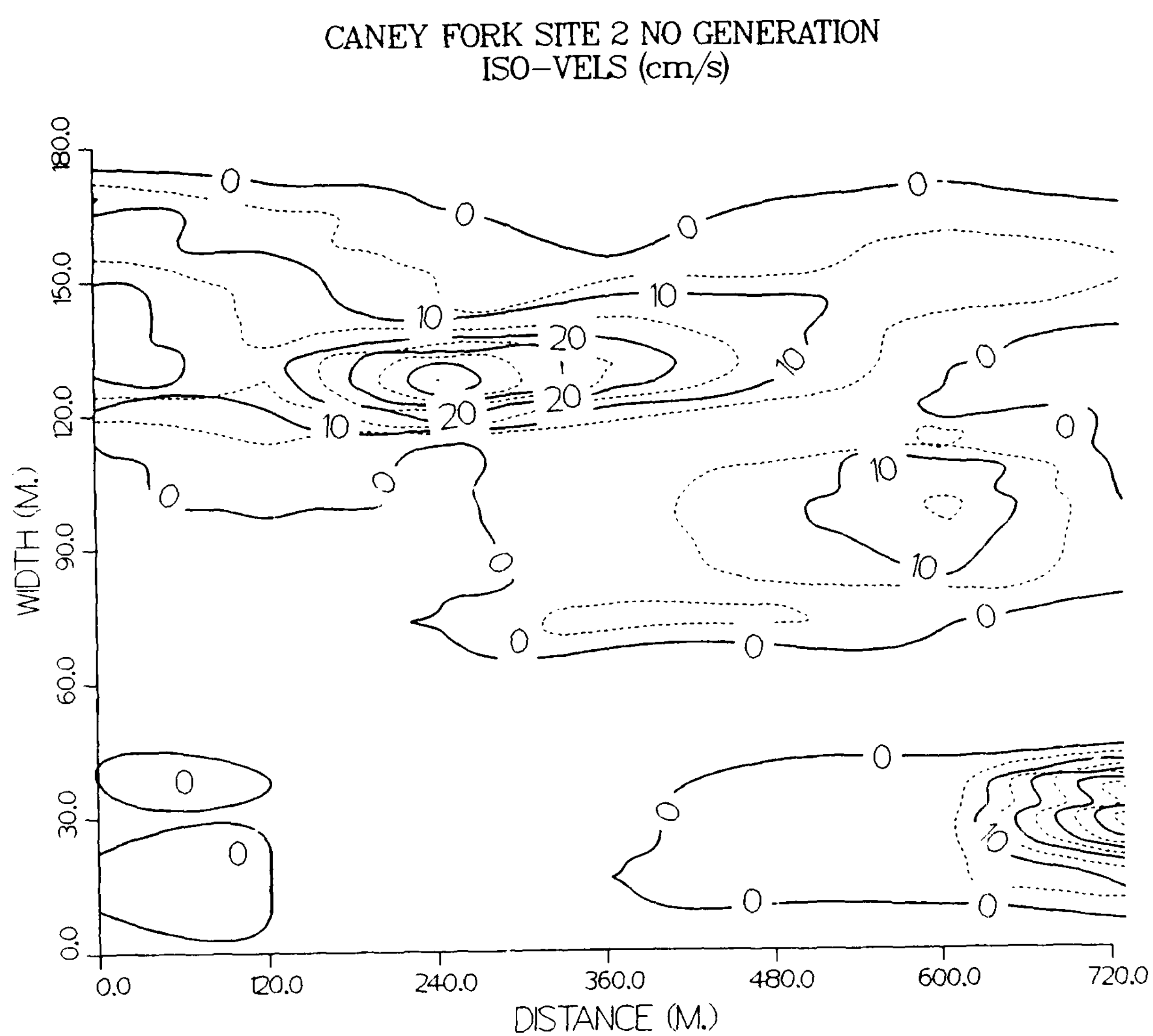


Figure 20. Site 2 flow patterns (isovels in 5-cm/sec intervals) during nongeneration

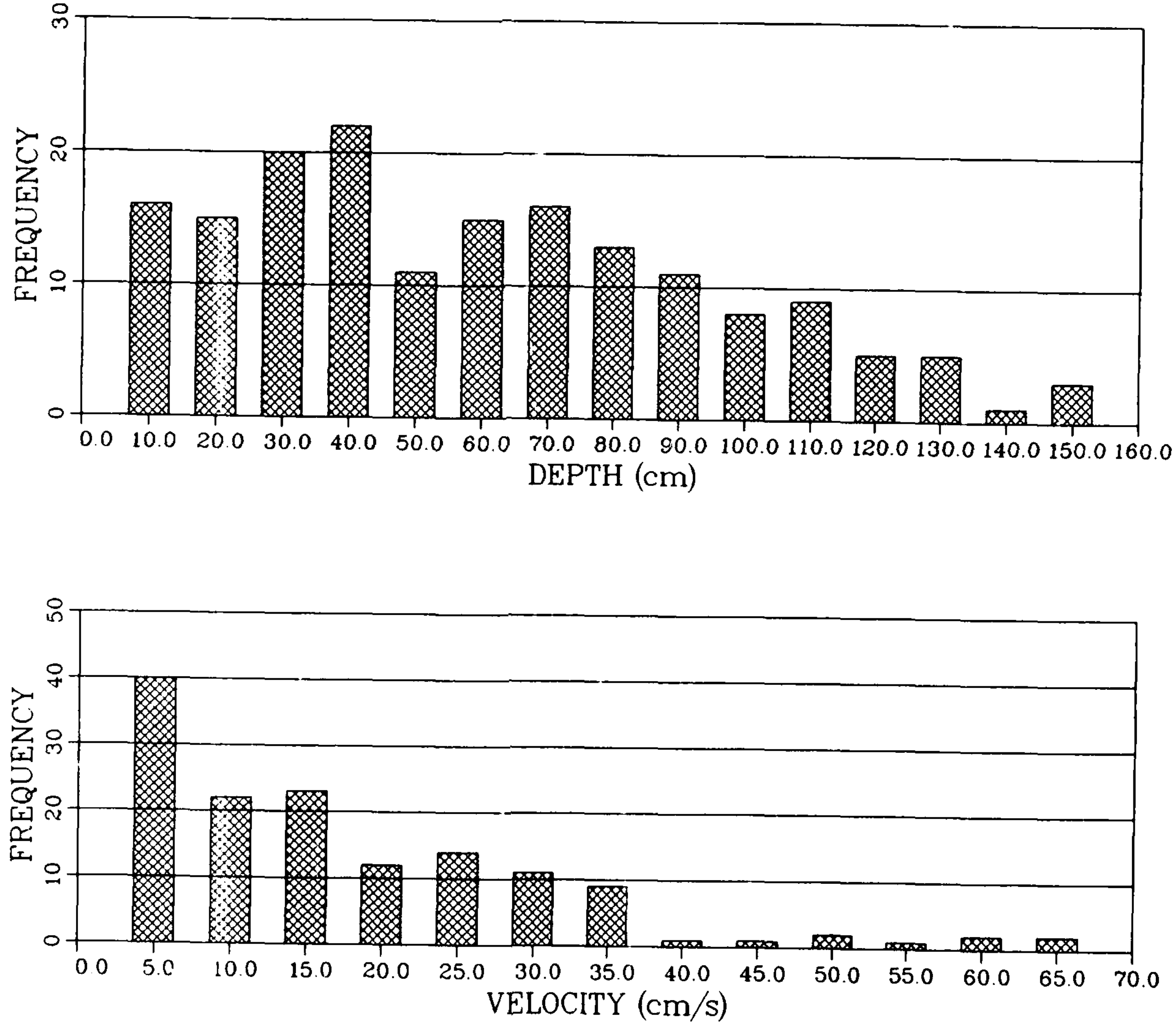


Figure 21. Frequency distributions of depth (10-cm increments) and velocity (5-cm/sec increments) at Site 2 during nongeneration

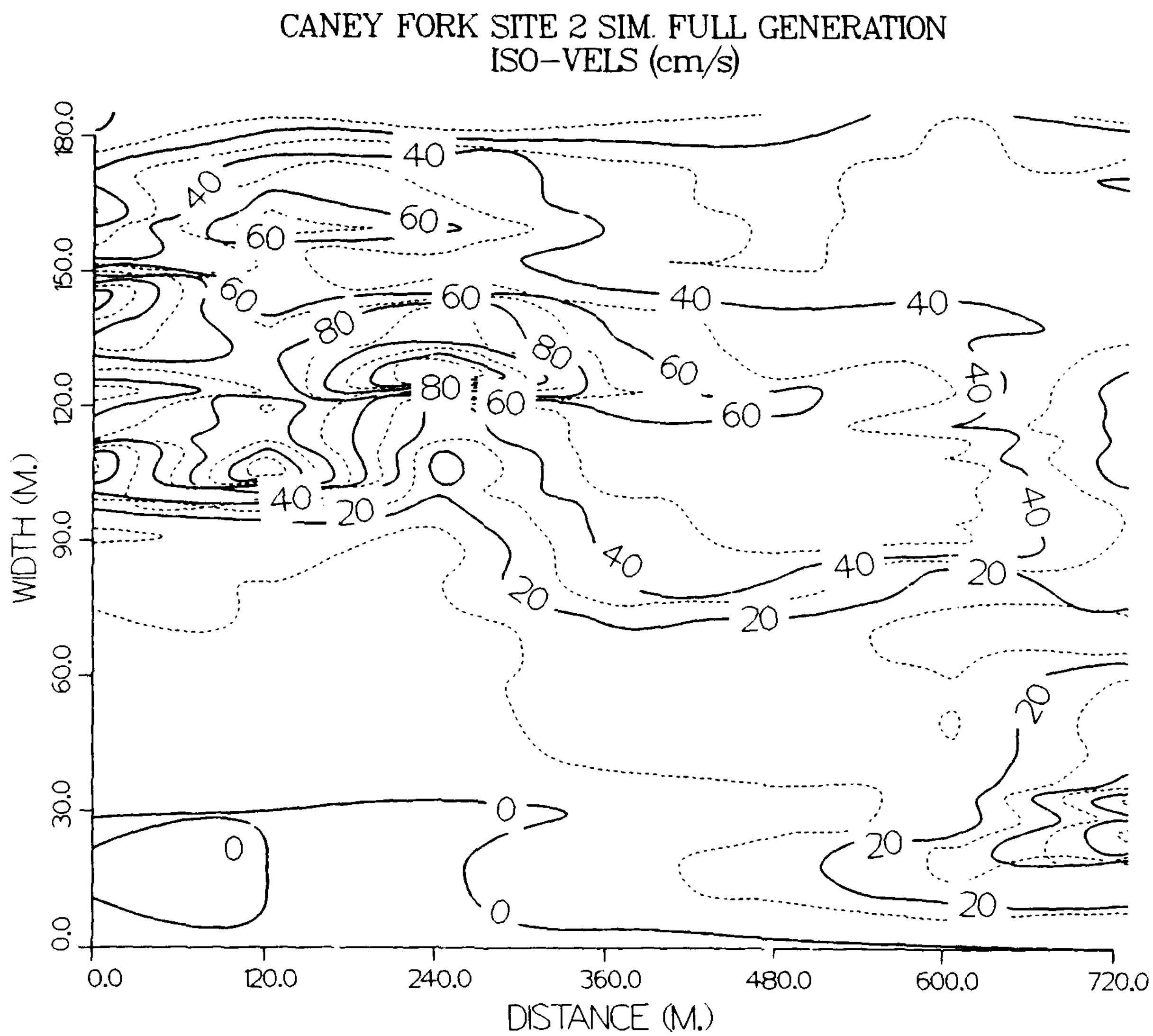


Figure 22. Site 2 flow patterns (isovels in 10-cm/sec intervals) at simulated full generation

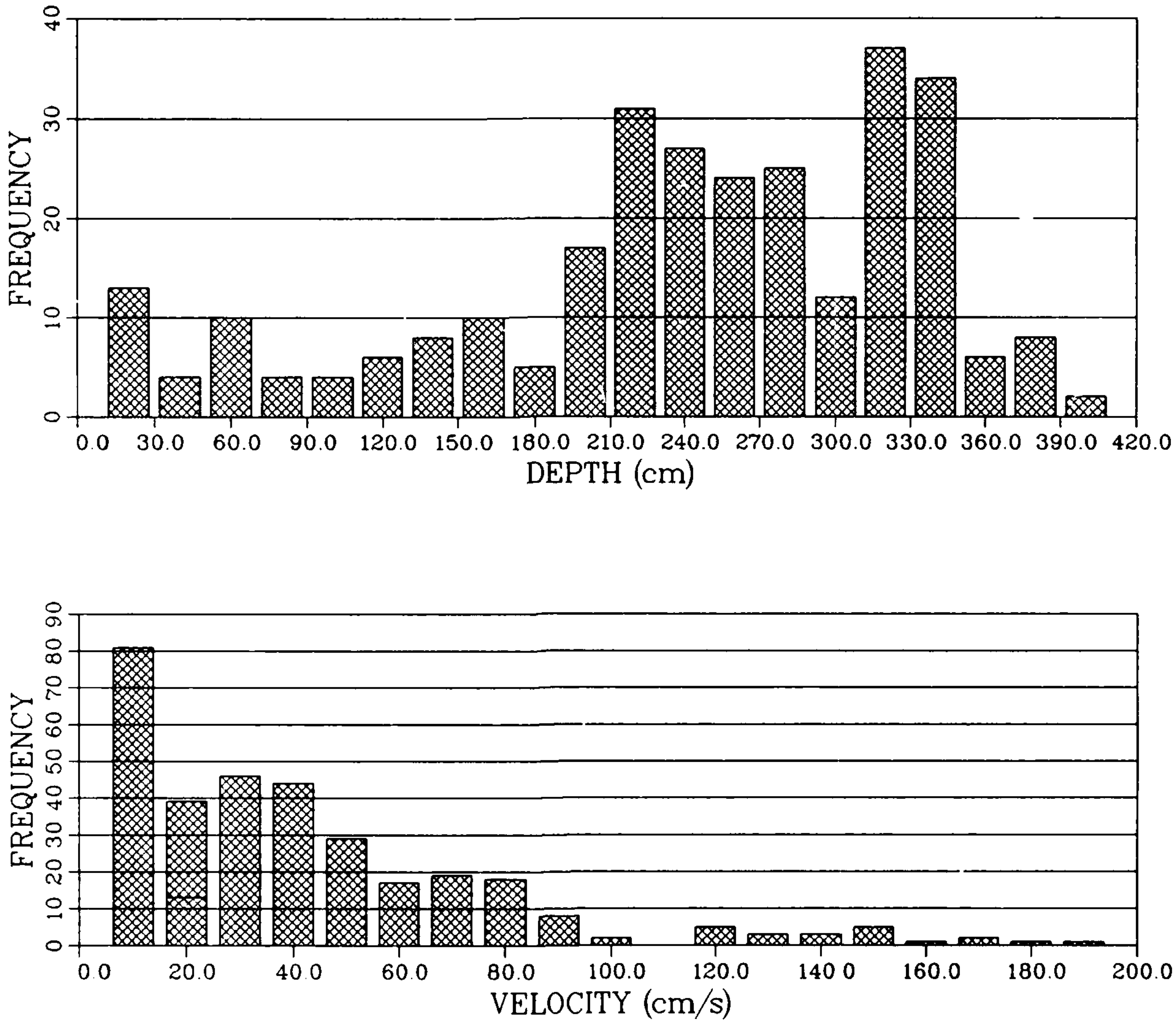


Figure 23. Site 2 frequency distributions of depths (15-cm increments) and velocity (10-cm/sec increments) during simulated full generation

75. Discussion and analysis. Statzner (1987) has predicted that areas of stream braiding would have the greatest diversity of hydraulic conditions available to aquatic biota. Plots of the frequency of distribution of various depth and velocity classes (Figure 21) would seem to support this observation, as velocity and especially depth distributions are much more heterogeneous when compared with Site 1 (Figure 17). Presumably, the diversity of depth and velocity combinations will allow a greater variety of shear stress conditions to exist, which, in turn, present greater habitat for a more diverse benthic community.

Site 3

76. Description. The effects of peaking hydropower operation at this site, located approximately 20 km downstream from Center Hill Dam, are considerably reduced compared with Sites 1 and 2. Stage differences between nongeneration and full generation are about 1.5 m. The river at Site 3 has a well-defined thalweg and a pool-riffle sequence typical of medium-order rivers. The substrate is composed of a mixture of boulder, small and medium cobble, and some sand and gravel (Figure 24). Site 3 contains a large deep pool over 3 m deep at low flows (Figure 25). Maximum velocities during nongeneration are no greater than 45 cm/sec, and flow is confined to a relatively narrow channel (Figure 26). Depths and velocities show little variation at low flows (Figure 27). The majority of depths are less than 60 cm with flows of 5 cm/sec or less. Despite the large pool, Site 3 exhibits more diverse physical habitat conditions than Site 1. At simulated full generation, the highest velocities follow the thalweg (Figure 28). As at Sites 1 and 2, full-generation flows in the channel (opposed to the overbank) produce generally homogeneous velocities and depths. Highest flows are approximately 120 cm/sec, and most depths range between 2 and 3 m (Figure 29). The majority of moderate velocities and depths occur along the edges of the channel and on the overbank that are dewatered during nongeneration.

77. Discussion and analysis. The pool probably acts as a refuge during peaking events since shear stress, turbulence, and velocity conditions will not change dramatically under moderate increases in flow. The large cross-sectional area available for conveyance in deep pools will dampen changes in flow normally associated with peaking hydropower operation.

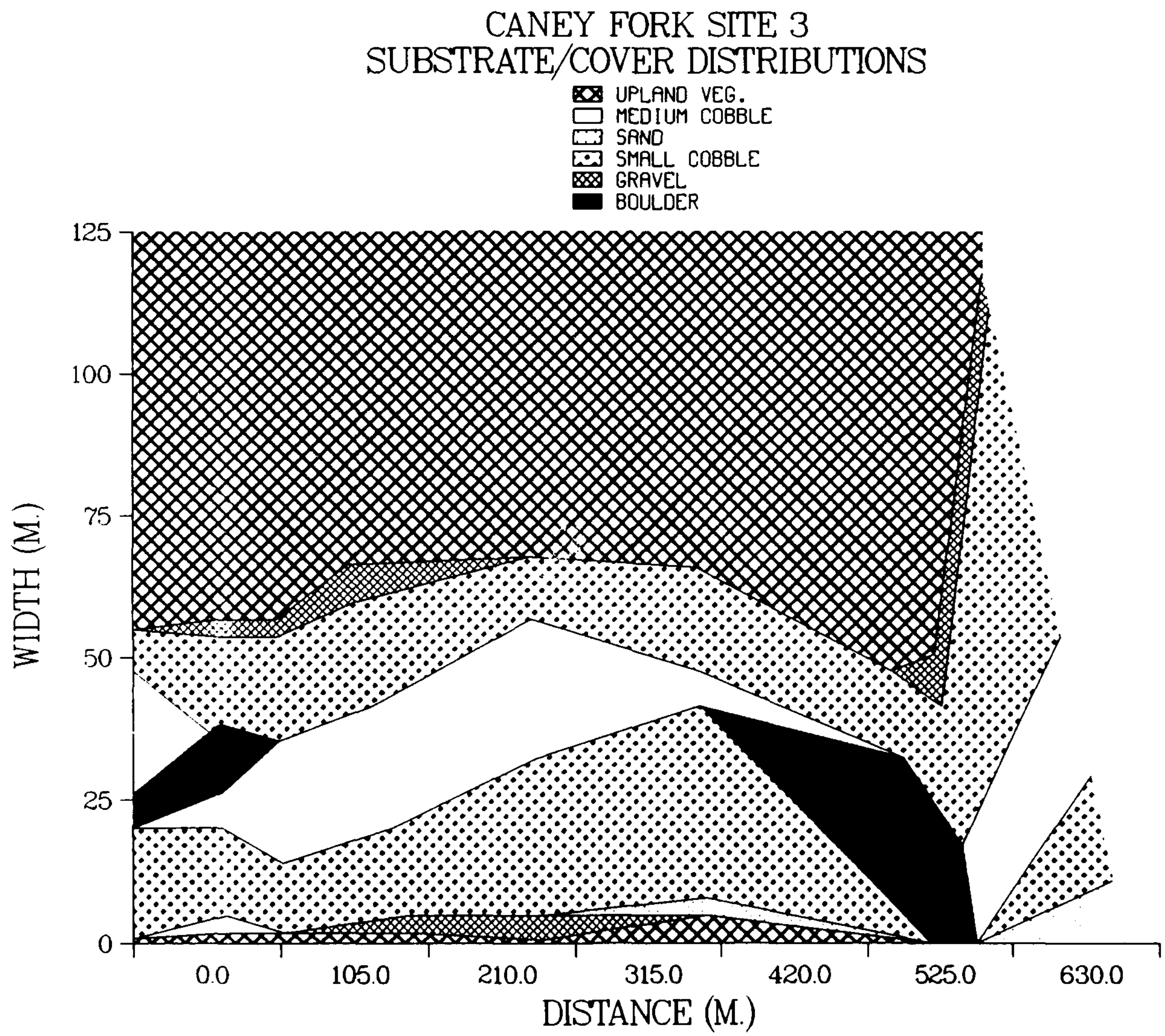


Figure 24. Site 3 substrate distributions

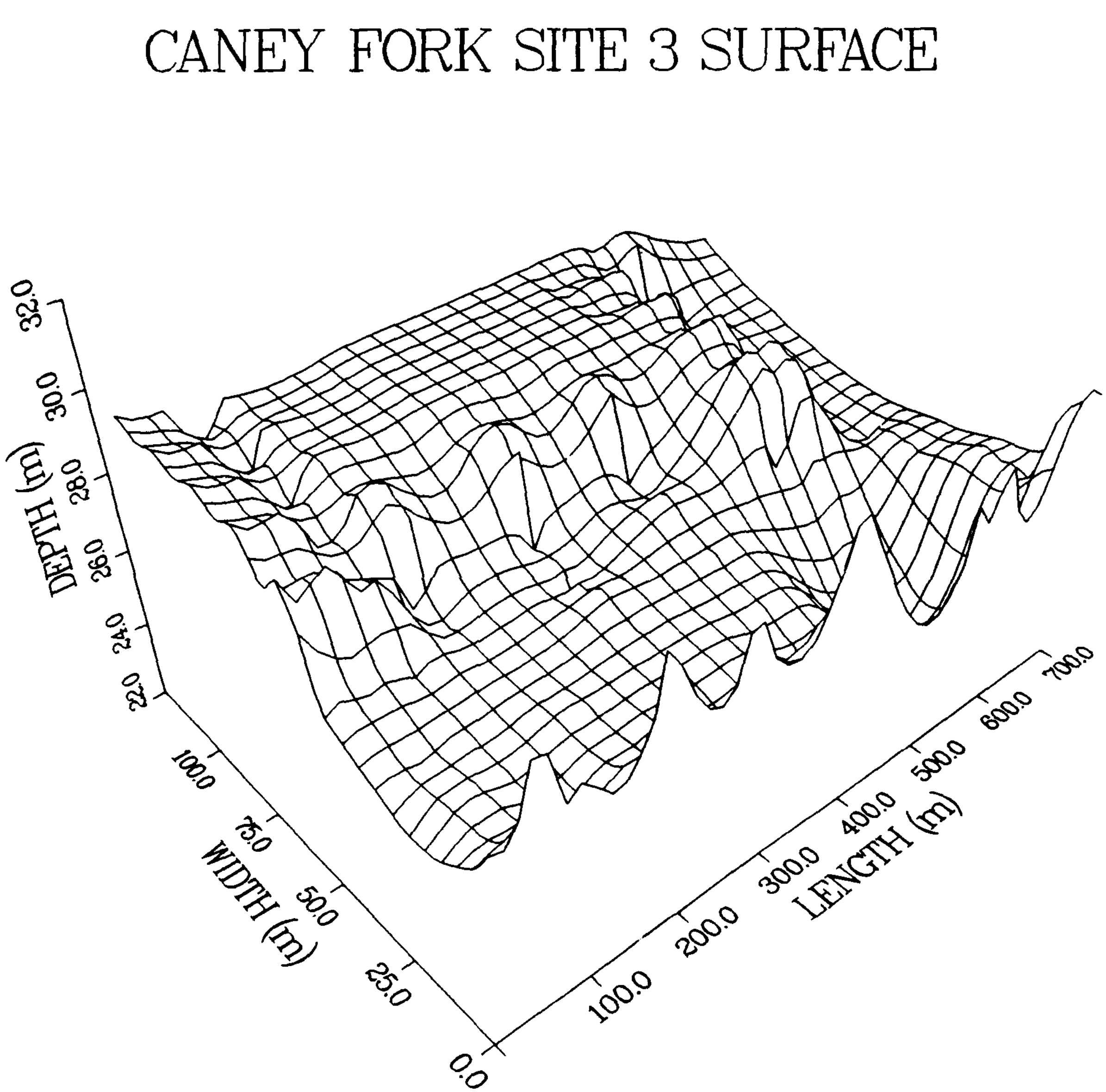


Figure 25. Site 3 bathymetry

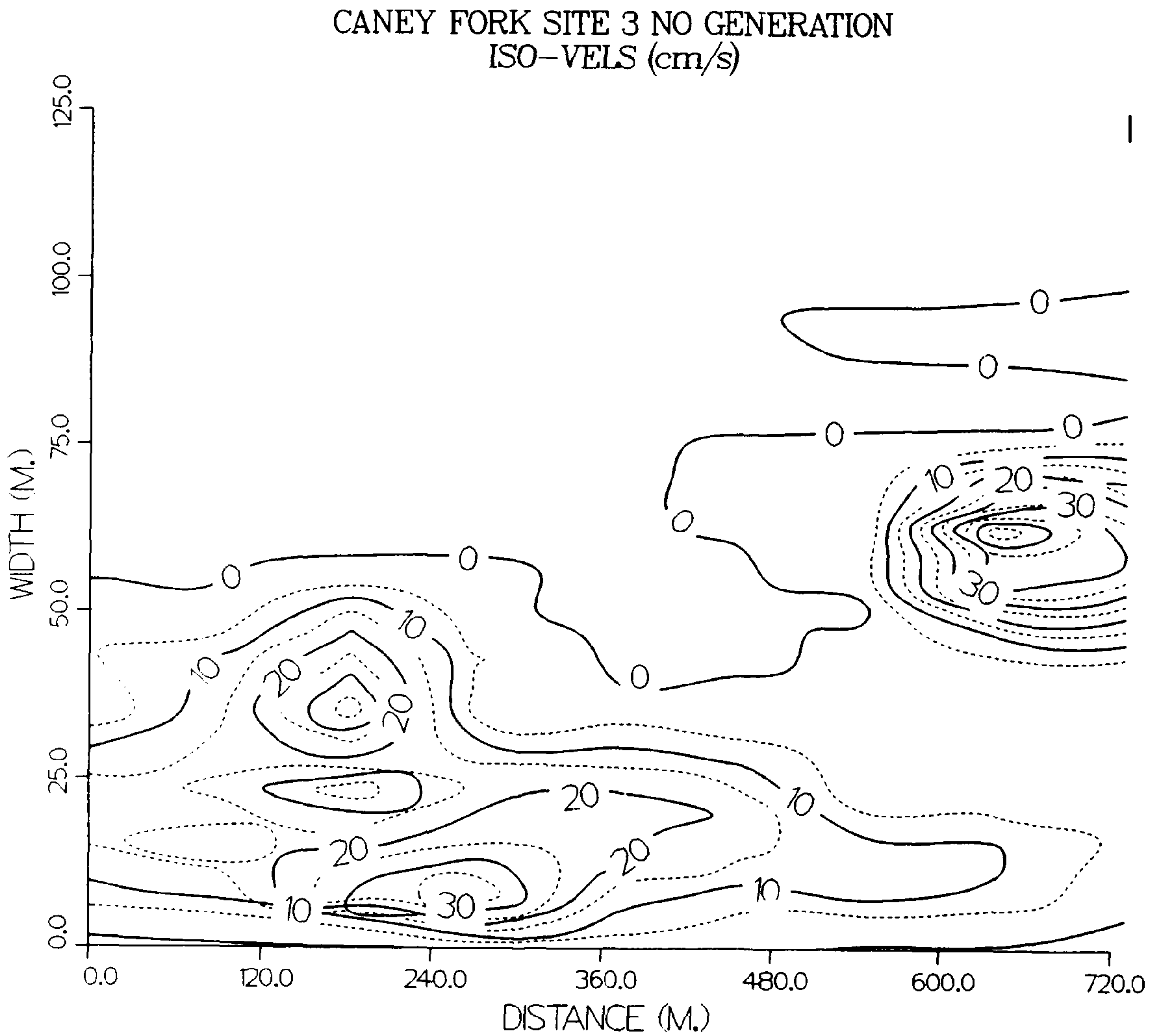


Figure 26. Site 3 flow patterns (isovels in 5-cm/sec intervals) during nongeneration

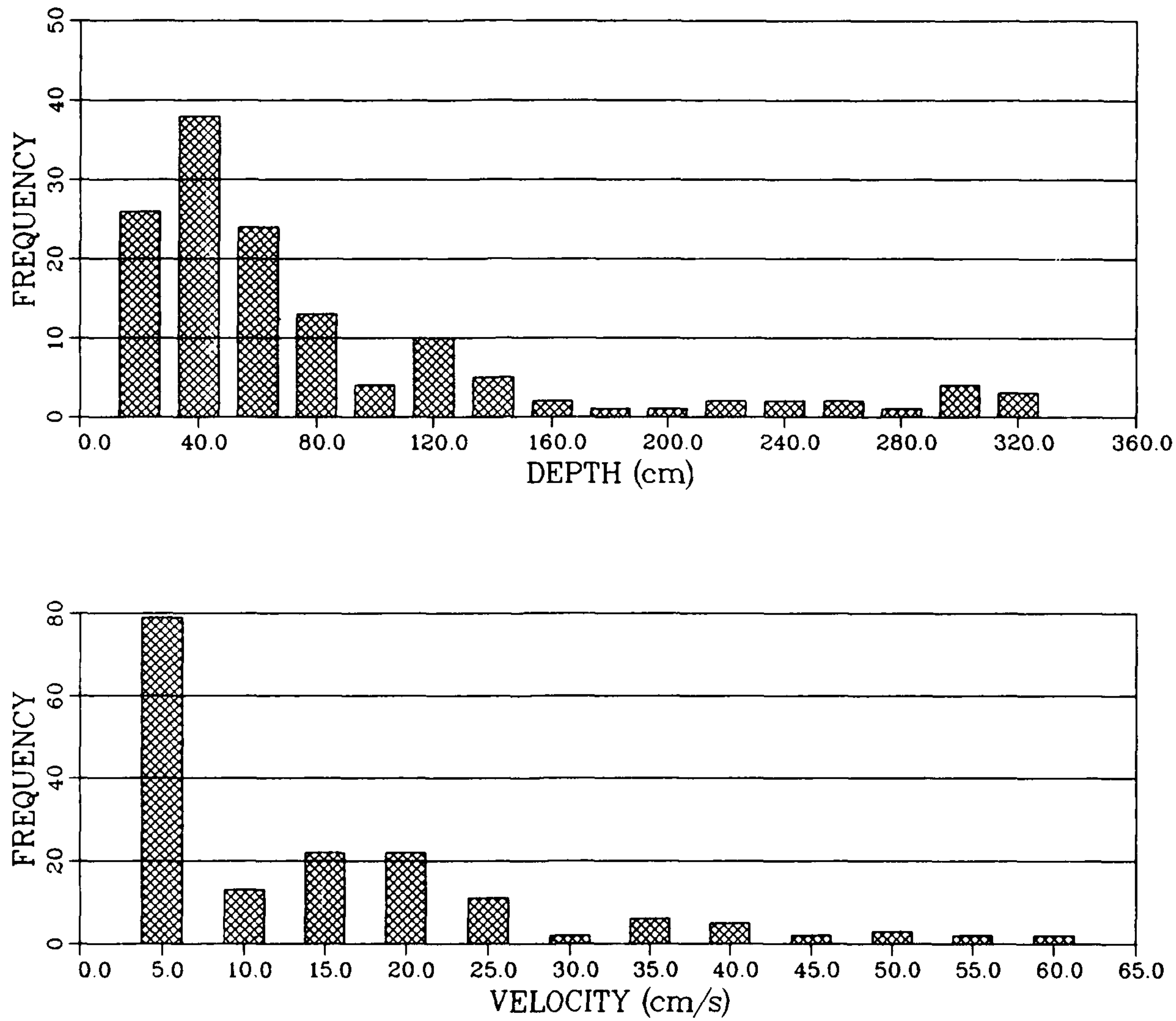


Figure 27. Site 3 frequency distributions of depth (20-cm intervals) and velocity (5-cm/sec increments) at Site 3 during simulated full generation

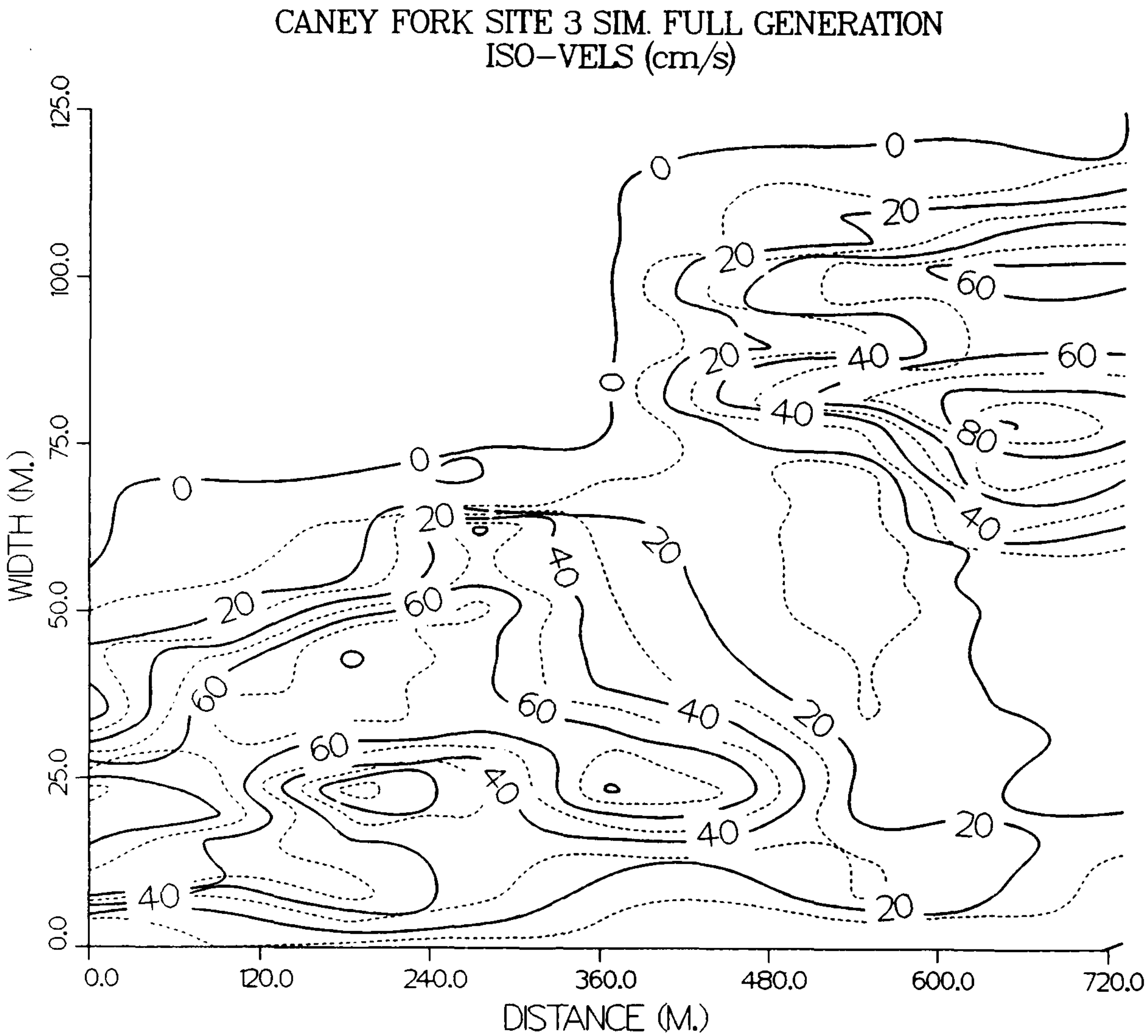
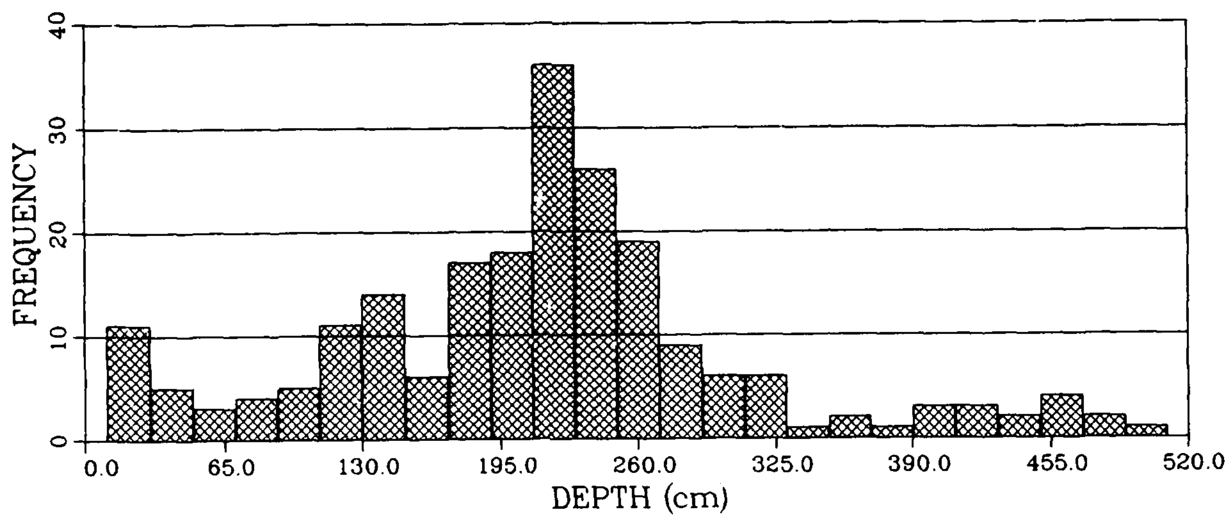


Figure 28. Site 3 flow patterns (isovels in 10-cm/sec intervals) during simulated full generation



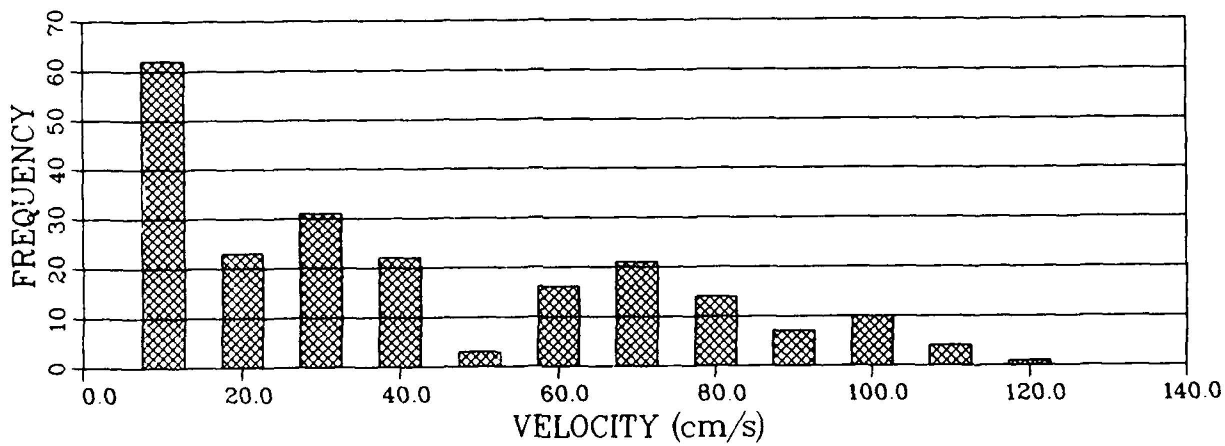


Figure 29. Frequency distribution of depth (25-cm increments) and velocity (10-cm/sec increments) at simulated full generation

General Discussion

78. These three sites exemplify habitat conditions of special concern downstream of peaking hydropower projects. Additionally, the gradient in peaking hydropower impacts across these three sites facilitates incremental analysis of the responses of aquatic biota. Sites 1 and 2 represent areas of impact in the upper reaches of the tailwater. Site 1 exhibits channel degradation, high velocities, rapid stage changes, and a thalweg that is deep and straight. Channel geometry resembles a highly channelized and armored stream. Site 2 is a zone of aggradation where sediments eroded from Site 1 are deposited. It is characterized by deposited fines, a meandering thalweg, and a channel geometry most typical of large, slow-moving braided streams. Finally, partial recovery to preimpoundment physical characteristics is observed at Site 3. It has a mixed substrate, a sinusoidal thalweg, and reasonably defined pool-riffle sequence. Although Site 3 does not exhibit the large-scale changes in stage found in more upstream areas, it is still influenced by fluctuating flows from peaking generation.

PART V: HABITAT EVALUATIONS FOR TAILWATER FISH SPECIES

Background

79. Habitat requirements of aquatic biota can be broadly classified into two categories of variables, each of which must be evaluated to assess the effects of water resources development. The first category includes water quality variables and temperature. In tailwaters, these variables (also referred to as macrohabitat variables) generally change only in the longitudinal dimension. Detailed assessments of water quality changes associated with peaking operation are not presented, although many of the general changes are discussed in Parts II and III of this report.

80. Although a stream section may provide suitable macrohabitat conditions throughout its length, the distribution of a species will not likely be uniform or random; instead, fishes will occupy specific locations in a stream based on substrate or cover and various combinations of hydraulic variables such as shear stress, depth, and velocity (Bovee 1982; Statzner, Gore, and Resh, in press). These variables (often referred to as microhabitat variables) can be used to describe the precise locations occupied by fish.

81. Macrohabitat information for many species is often readily available in published life-history information; however, this is not usually the case for microhabitat information. Furthermore, microhabitat selection by a species may be influenced by the presence of other species (Fausch and White 1981, Finger 1982). Therefore, even when microhabitat information is available, it is often preferable to develop a site-specific data base because such information can account for existing biological interactions (Nestler, Milhous, and Layzer, in press).

82. A variety of techniques for obtaining microhabitat information is available to stream researchers. These include electrofishing, stream bank observation, radiotelemetry, and instream observation by snorkel and scuba. Bovee (1986) discussed the advantages of these various techniques and suggested that direct observation of fish by skin diving or scuba may be the best technique to employ if visibility is sufficient and necessary safety precautions are taken. This technique is frequently used for observation of salmonids and has been successful in a number of recent studies. Greenberg and Holtzman (1987) reported that snorkeling was an effective method for

censusing banded sculpin (*Cottus carolinae*) populations and determining their microhabitat requirements in streams in east Tennessee.

Model Species Selection

83. The objective of this study is to identify important habitat factors in tailwaters and to illustrate how the impacts of reservoir operation can be assessed. To meet these objectives, two species of fishes were selected for detailed investigation: the banded sculpin and rainbow trout. These two species are presented as examples to aid in model development for other species because of their widely varying habitat requirements. The banded sculpin is a benthic fish that utilizes gravel and cobbled substrates with shallow depths under low to moderate velocities. It is a sight-oriented predator that feeds primarily upon benthic macroinvertebrates. In contrast to the banded sculpin, rainbow trout have a preference for deeper, slow-moving waters with complex cover structures such as boulders, bedrock outcroppings, and flooded upland vegetation (Nestler et al., in preparation). Rainbow trout are sight-oriented predators that feed on drifting benthic macroinvertebrates and small forage fish within the water column.

Field Techniques

84. Information on the microhabitat utilization of banded sculpin and trout was collected by underwater observations made at the three sampling sites during low-flow conditions (no generation). Two divers swimming parallel to each other moved slowly either upstream (banded sculpin) or downstream (rainbow trout) in a zig-zag pattern. When they encountered large cobble or small boulders (relatively uncommon), the divers overturned the substrate to search for sculpins. With experience, the divers were able to observe the sculpins in the clear waters of the Caney Fork River even though sculpins are a benthic species with cryptic coloration. The divers placed a weighted marker at the precise location occupied by each sculpin or trout that held its position and did not exhibit any signs of alarm. Each marker was coded and had a fluorescent ribbon attached to facilitate relocation of all markers. Prior to placing the marker, the diver estimated the total length of the sculpin using a plastic ruler placed near the fish. Only the area between

two or three transects could be effectively sampled in 1 day. The diver also noted (on aluminum tags attached to the markers) if the trout was occupying the top, middle, or bottom third of the water column along with a rough estimate of total length.

85. After the diving session was completed, each marker was relocated. At the precise location of each marker, water depth was measured and velocity determined with a Marsh-McBirney current meter at 0.2, 0.8, and 0.9 × depth. The substrate/cover was observed within a radius of 0.25 m, and a coded value (Table 2) was assigned and recorded. For a representative sample of observations, velocities at 0.9 × depth were also measured at points one body-length (~160 mm) away from the exact location of the fish in four directions (upstream, downstream, and each side).

86. Habitat utilization data were field measured at each of the three study sites. Habitat availability data were synthesized based on hydraulic measurements made along each transect during the low-flow period.

Developing Suitability Criteria

87. Frequency-of-use histograms for each microhabitat variable were constructed as a first step in developing habitat suitability criteria for banded sculpin and rainbow trout. Examination of these frequency distributions indicates distinct clustering of observations around particular values of each variable. For instance, nearly one-half of the sculpins observed were found over a gravel-cobble substrate (Figure 30), and twice as many fishes occurred at water velocities less than 3 cm/sec compared with any other velocity category (Figure 31). While a wide range of depths was used by sculpins, more than 90 percent of the fishes were found at depths less than 70 cm (Figure 32).

88. Habitat suitability criteria based solely on utilization data could result in erroneous conclusions regarding the habitat preferences of a species. For example, less than 5 percent of the sculpins observed were found where boulders were present. From this low frequency of use, one might infer that areas with a boulder substrate are suboptimal habitat for sculpins. However, a cursory inspection of the substrate distributions for the three study sites indicates that boulder substrata were rare (Figures 11, 18, and 22). Thus, the low frequency of boulder substrate use is likely related

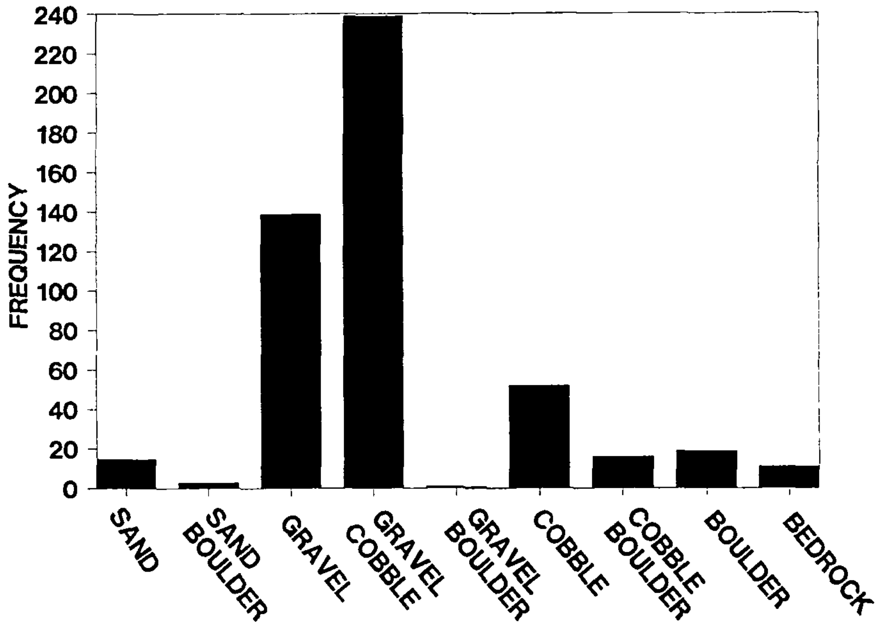


Figure 30. Frequency distribution of banded sculpin (*Cottus carolinae*) utilizing various substrate/cover types

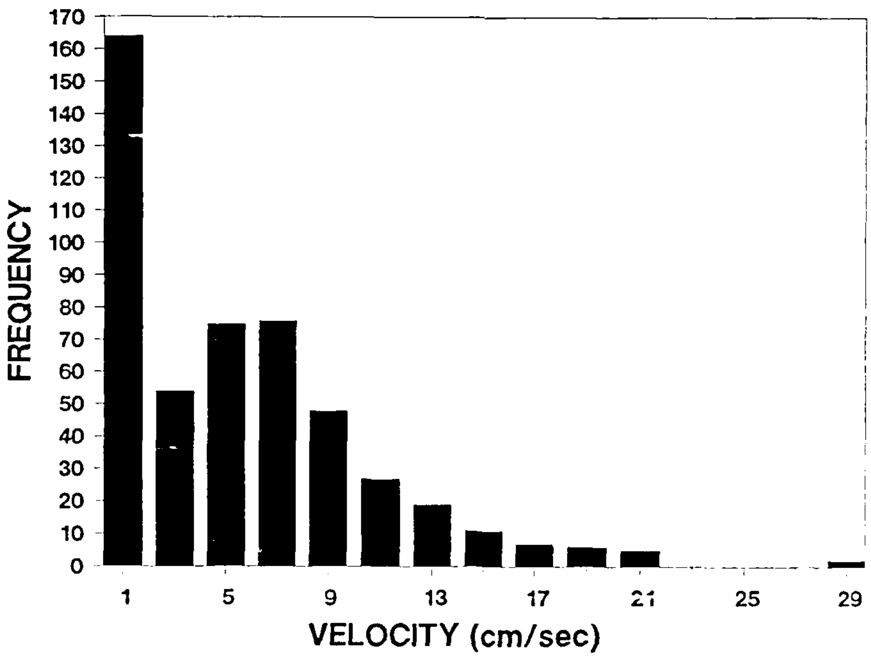


Figure 31. Frequency distribution of banded sculpin (*Cottus carolinae*) utilizing various velocities (increments of 2.5 cm/sec)

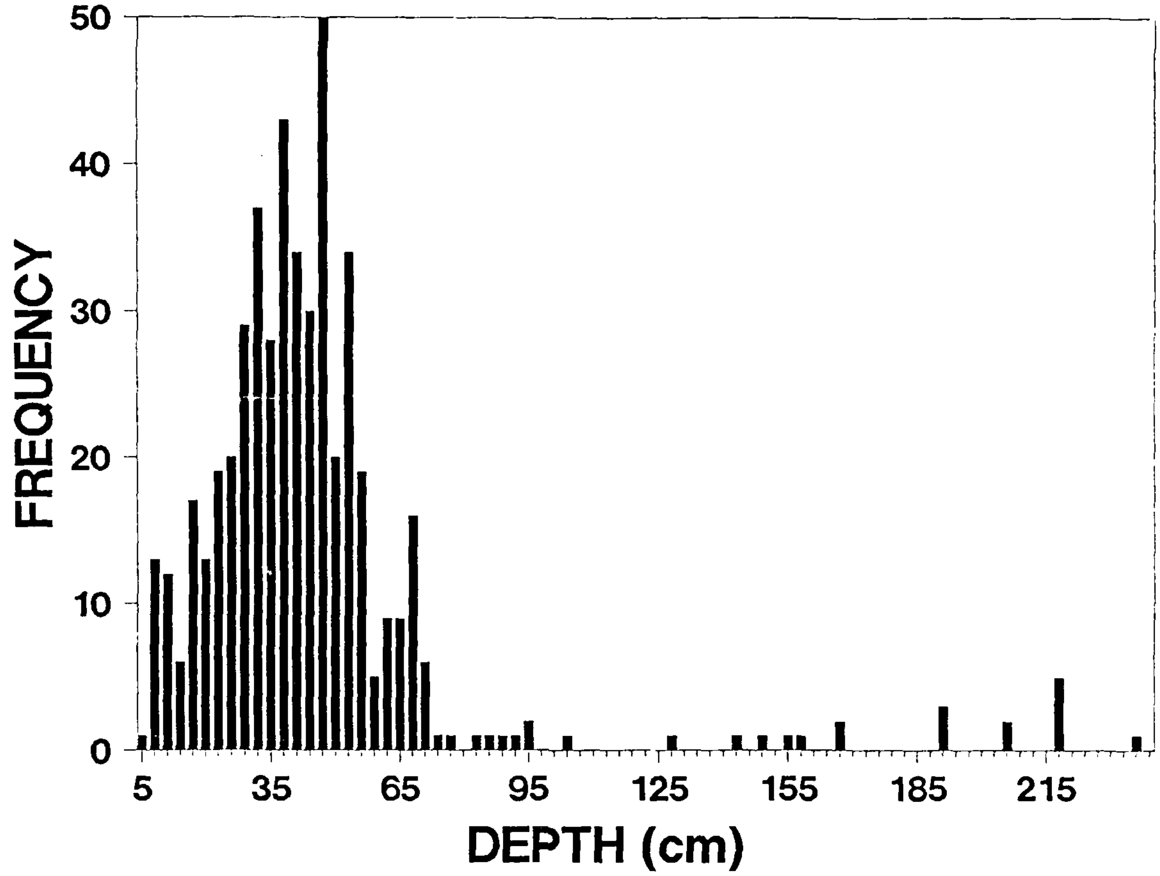


Figure 32. Frequency distribution of banded sculpin (*Cottus carolinae*) utilizing various depths (increments of 2.5 cm)

to the low availability of that type of habitat and is not a reflection of suitability. To overcome the difficulty in interpreting the utilization data, the investigators adjusted all habitat use data for the relative frequency of each value of the microhabitat variables in the study area; i.e., they calculated proportional use values (Pi) in the following manner:

$$Pi = \frac{ni/N}{Vi/Vt} \qquad (1)$$

where

ni = number of sculpins or trout observed in the i^{th} category of variable V

N = total number of sculpins or trout observed

Vi = frequency of occurrence of the i^{th} value of variable V (determined from measurements made along all transects at the three sites)

Vt = total number of all measurements of variable V made along the transects

89. Finally, the researchers normalized the proportional use values by dividing all Pi values by the maximum Pi value for each variable. This procedure results in assigning a maximum suitability value of 1.0 to optimal habitat and a value of 0.0 to unsuitable habitat. Details of this technique and the statistical interpretation of these types of data can be found in Bovee (1986).

90. The suitability criteria developed by this procedure for substrate indicate that optimal habitat for sculpins can occur over a broad range of substrate types (Figure 33). The low suitability values for bedrock and sand may be related either to inadequate concealment or lack of hydraulic refuge provided by these substrates. Suitability criteria developed for velocity at 0.9 × depth suggest that sculpins may have a relatively limited tolerance for high bottom velocities (Figure 33) or shear stresses. Although sculpins utilize a broad range of depths, optimal depths occurred over a much narrower range (Figure 33).

91. Suitability criteria developed for adult rainbow trout (Figure 34) are fairly typical of rainbow trout (Bovee 1978). However, the velocity preferences are more typical of those attributed to spawning habitat than for maintenance habitat. Rainbow trout, like many other aquatic biota, appear to be sufficiently plastic in their habitat requirements so that they can adjust to local flow and cover conditions. These contrasting results point to the conclusions of many IFIM researchers who maintain that onsite development of habitat suitability criteria will yield the best habitat predictions (Bovee 1986, Cada et al. 1983, Gore and Nestler 1988).

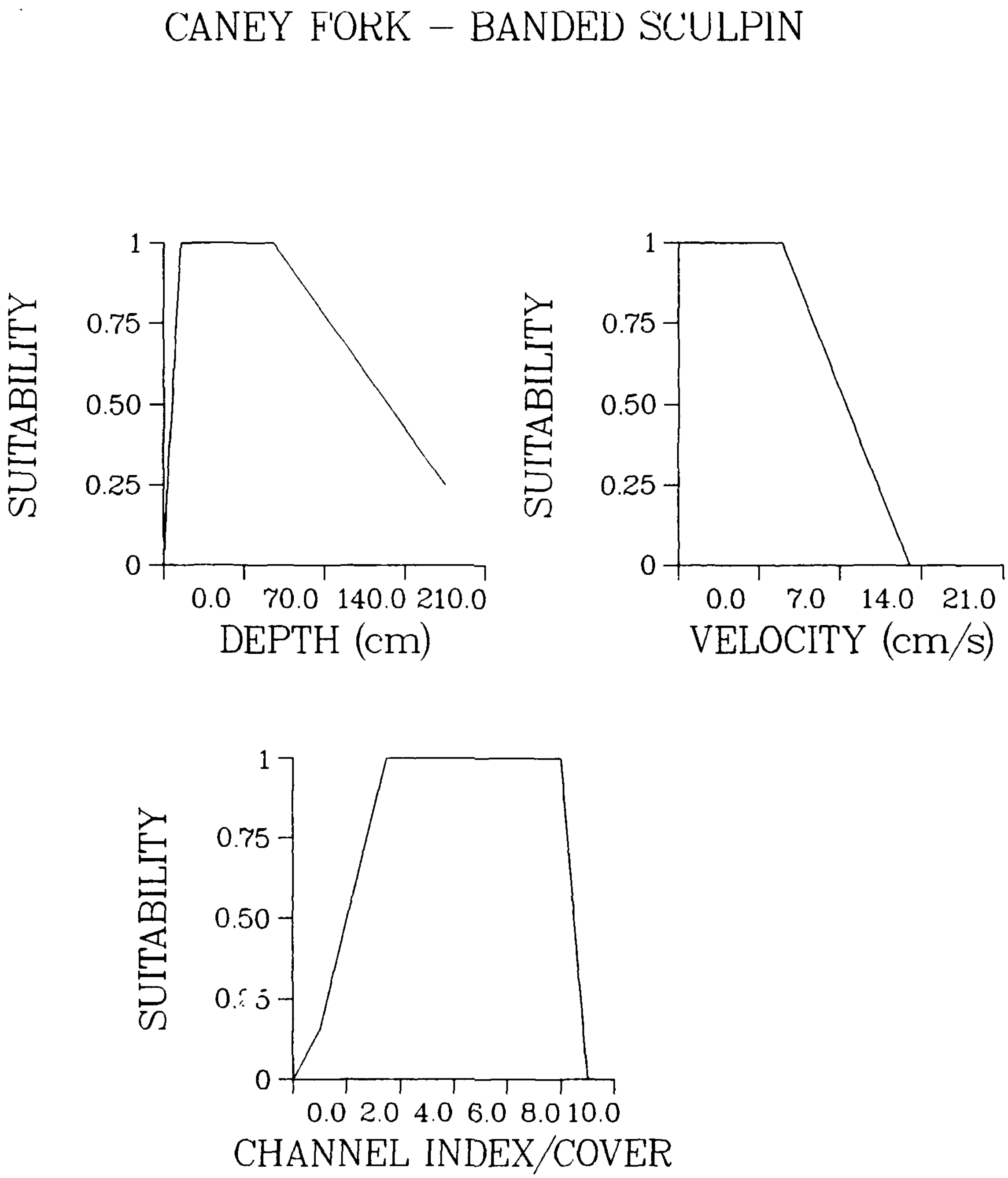


Figure 33. Habitat suitability curves for banded sculpin (*Cottus carolinae*) in the Caney Fork River

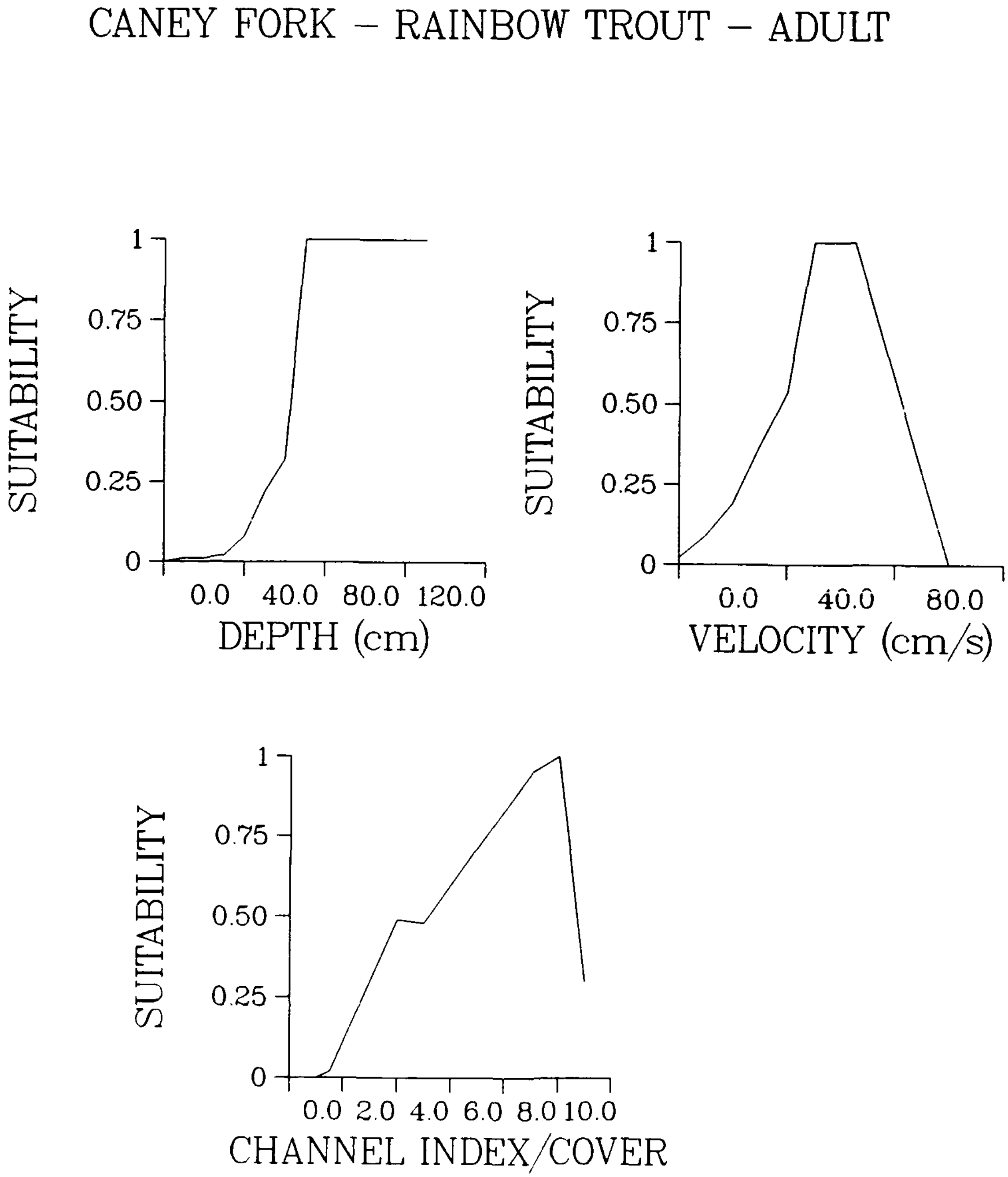


Figure 34. Habitat suitability curves for rainbow trout (*Salmo gairdneri*) in the Caney Fork River

PART VI: PREDICTION OF PEAKING IMPACTS ON BIOTA

Methods of Analysis

Steady-state simulation

92. Field observation and literature information indicated that the PHABSIM system of the IFIM, with some modification, would adequately describe the habitat features required by both fish species as well as serve as a framework to describe their response to peaking hydropower operation. Although a variety of methods is available within PHABSIM to provide streamflow description for habitat assessment, the "IFG-4 program using a single calibration flow" method (Milhous 1986; Milhous, Updike, and Schneider 1989) was selected because it optimizes accuracy and ease of application.

93. This method approaches flow description in two steps. First, a stage-discharge relationship is required. The relationship can be obtained by using programs within PHABSIM, by using hydraulic programs such as HEC-2, from a gage, or by field determination. For this work, stage-discharge information was obtained from gages established by the ORN at each of the sampling sites.

94. After a stage-discharge relationship is obtained, the IFG-4 program can be used to partition flow at each separate discharge into a series of lateral cells at each cross section. Velocity calibration measurements are made in the field under constant discharge. Calibration data were measured at all transects from low-flow analyses used in habitat descriptions. The measured velocities are used to solve for a bed-roughness coefficient (Manning's n) for each lateral cell in Manning's equation since all other variables are known. The calculated cell-specific n values are then used to generate velocities in each cell at all simulated discharges by solving Manning's equation. Depths are calculated using a stage-discharge relationship. After estimating a lateral flow pattern, the IFG-4 program compares its calculated water surface elevation with the given water surface elevation provided in step 1. If needed, the IFG-4 program modifies all cell velocities by a common factor to raise or lower calculated water surface elevations to match elevations provided in step 1. Caution must be exercised in selecting a calibration flow. If the user suspects a shift in flow pattern with discharge, then additional velocity-calibration information may be required. A full description of this approach may be found in Curtis, Nestler, and Martin

(1987); Martin, Curtis, and Nestler (1985); and Nestler et al., in preparation.

95. In a typical application of PHABSIM, the program HABTAT uses the values for depth, velocity, and substrate/cover in each cell compared with suitability values for the target species to generate a weighing factor for the surface area of the river represented by that cell:

$$W(i) = suit(d) \times suit(v) \times suit(c) \tag{2}$$

where

$W(i)$ = weighing factor for cell (i)

$suit(d)$ = suitability of the depth in cell (i) for a given discharge for the target species

$suit(v)$ = suitability of the velocity in cell (i) for a given discharge for the target species

$suit(c)$ = suitability of the substrate/cover in cell (i) for the target species

The amount of river area available for a target life stage in cell (i) can be represented as:

$$WUA(i) = area(i) \times W(i) \tag{3}$$

where

$WUA(i)$ = weighted usable area of the river surface represented by cell (i)

$area(i)$ = area of the river represented by cell (i)

$W(i)$ = weighing factor for cell (i)

The total Weighted Usable Area (WUA) in the study reach available for use by the target life stage for a given discharge can then be represented as the sum of the weighted areas of each cell or:

$$WUA(t) = \sum WUA(i) \tag{4}$$

where

$WUA(t)$ = total WUA for a given life stage

$WUA(i)$ = WUA in cell (i)

This formulation allows estimation of a single habitat value that is a function of discharge for the target species. Habitat available at other

discharges is calculated in a similar manner to generate an available habitat versus discharge relationship.

Dynamic flow habitat simulation

96. Conceptually, the Caney Fork analysis by PHABSIM under dynamic flow conditions is similar to the approach discussed in paragraphs 92-95, except that the range of discharges is instead replaced by a time series of discharges representing the flows at time increments over a generation cycle. Consequently, results for a single cross section are presented as habitat available per time increment rather than as a function of discharge, the normal method in instream flow analyses.

97. This report presents the generation schedule of 30 October 1987 (Figure 9) as typical of releases from Center Hill Dam. Maximum stage differences between full generation and nongeneration were 2.5 m at Site 1, 2 m at Site 2, and 1.5 m at Site 3. Results of habitat analyses are converted to a common standard (WUA/100 m of river length) because distances between transects are variable.

Interpretation of Results

Banded sculpin

98. At Site 1, maximum habitat for banded sculpin occurred on the rising and falling limbs of the generating cycle (Figure 35). In other words, habitat minima occurred during nongeneration low flows and during maximum generation. This pattern probably reflects the depth preference of banded sculpins (20 and 80 cm). More of these depths are available during the rising and falling limbs of the generating cycle than at low or high flows. A total of four peaks in habitat was observed since two generation periods were simulated. This pattern of dual peaks continued from transects 1 through 4. At low flow, the channel upstream of the tributary is characterized by a large gravel bar that is dewatered during nongeneration and a small, deep pool. Neither the gravel bar nor deep pool is considered optimum habitat for sculpin. Full generation resulted in a substantial loss of available habitat (e.g., a 75-percent reduction at Transect 6).

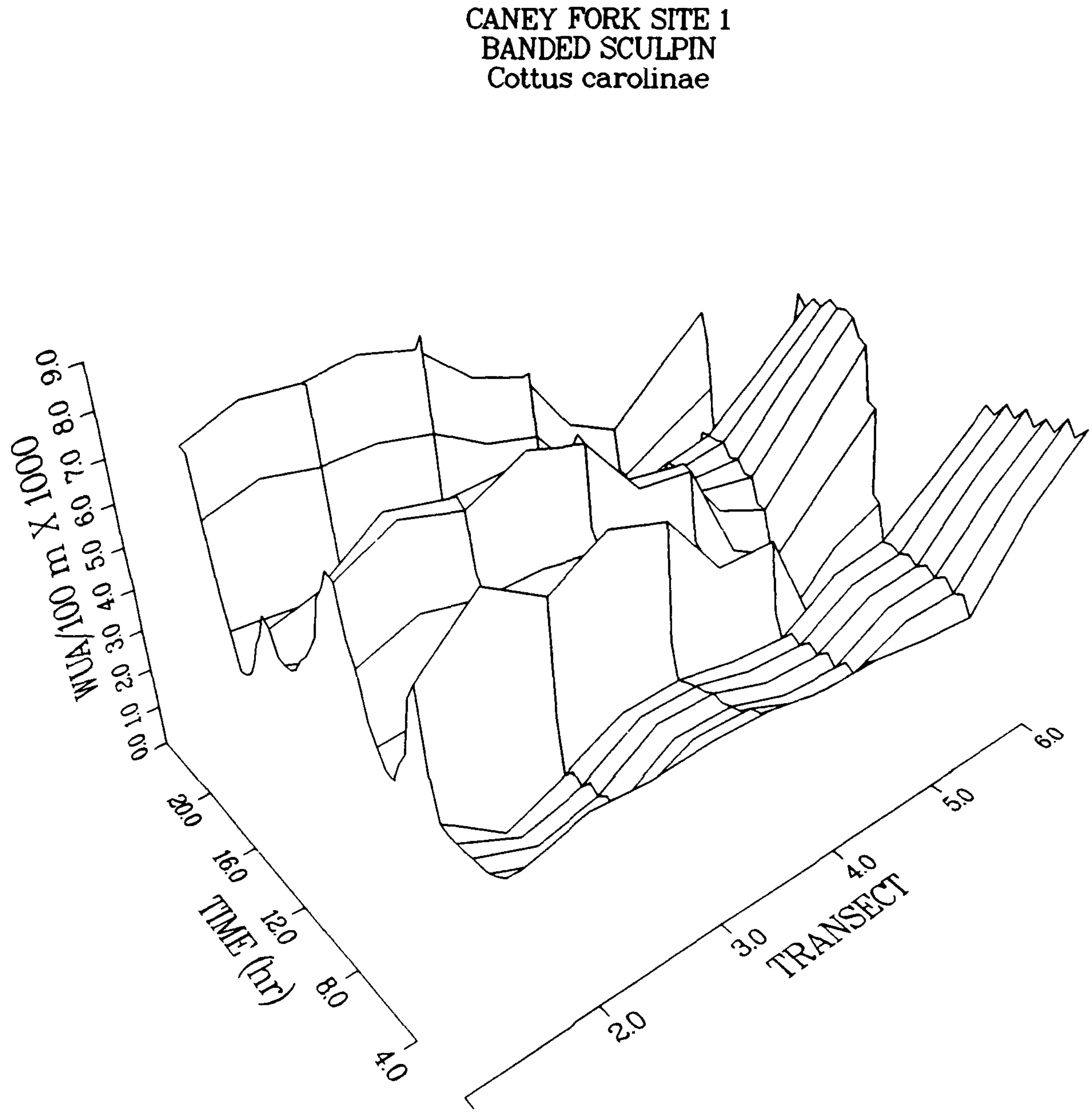


Figure 35. Adult banded sculpin (*Cottus carolina*) WUA/100 m of stream versus river mile for Site 1 on the Caney Fork River

99. At Site 2, loss of amplitude of the sharp peaks and valleys in habitat compared with Site 1 reflects the attenuation of the peaking wave as it moves 8 km downstream from the dam (Figure 36). Habitat losses during generation compared with habitat maxima were less than 70 percent (average of 66 percent) for all transects (Figure 36). Compared to transect 1, transect 5 consistently exhibits the greatest amount of available habitat at both high and low flows. In fact, minimum habitat values (at highest stage) at this

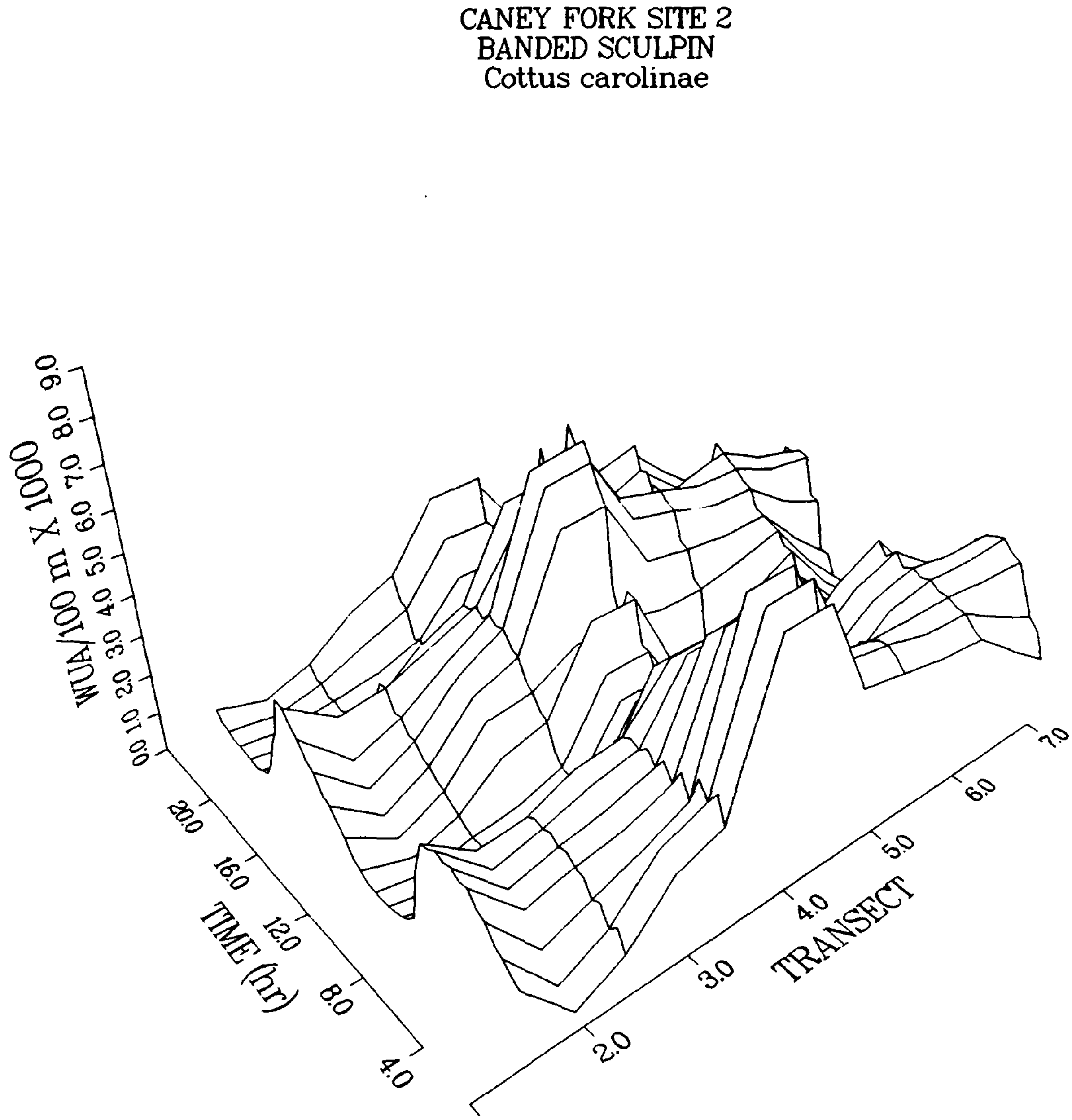


Figure 36. Adult banded sculpin (*Cottus carolinae*) WUA/100 m of stream versus time versus river mile for Site 2 on the Caney Fork River

transect approach habitat maxima observed at other transects for this site. Increased habitat availability at Transect 5 is related to channel conditions. This transect crosses the channel in a particularly wide part of the river in an area of considerable braiding. It also exhibits a wide variety of depths and velocities at all discharges compared with other transects, although conditions tend to become more homogeneous at higher flows.

100. At Site 3, compared with Sites 1 and 2, substantial attenuation of

peaks and valleys in habitat reflects the further attenuation of the peaking wave as it moves 20 km downstream from the dam (Figure 37). Habitat losses during the generation period were less than 50 percent except for Transect 9, which is a shallow riffle area that spreads laterally during the generation period accompanied by increasing velocities. Shallow, high-velocity areas provide relatively poor habitat for sculpin. The total amount of available habitat for sculpin under all discharges is substantially lower for Site 3

CANEY FORK SITE 3
BANDED SCULPIN
Cottus carolinae

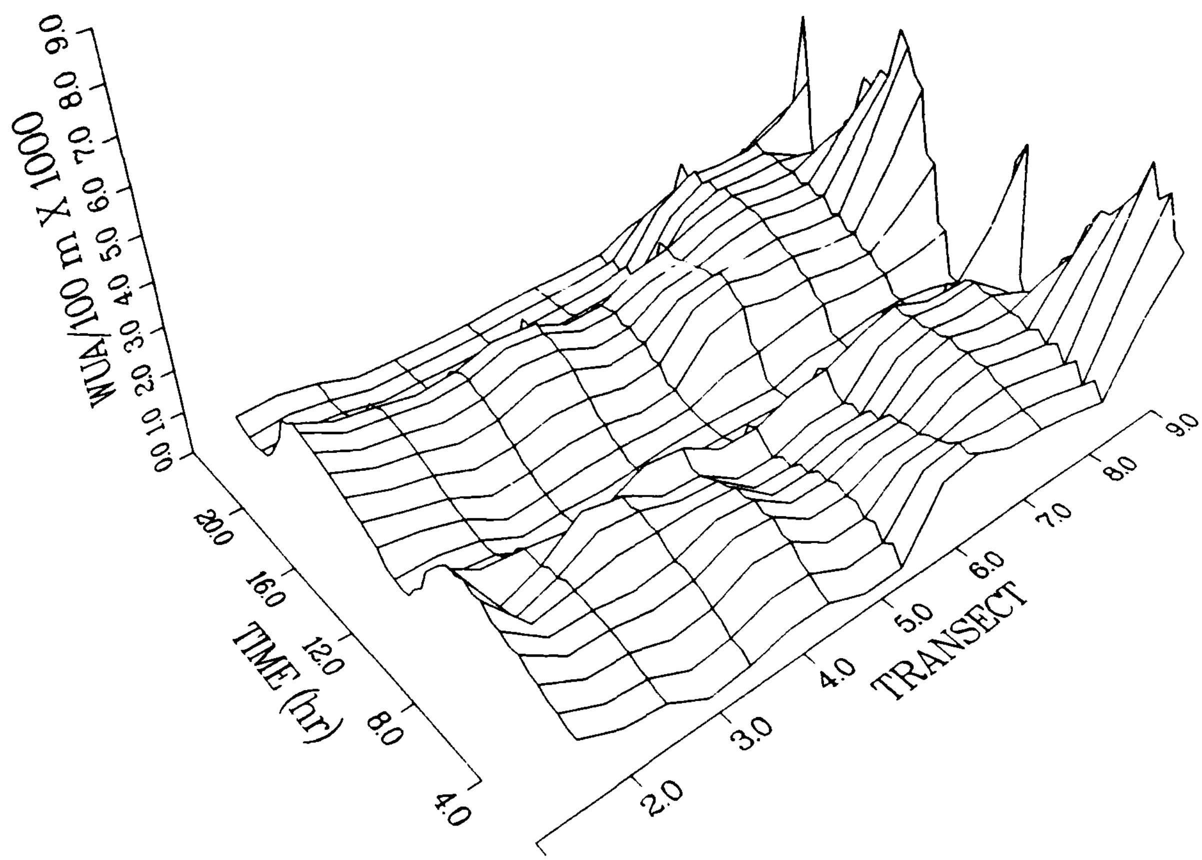


Figure 37. For adult banded sculpin (*Cottus carolinae*) WUA/100 m of stream versus time versus river mile for Site 3 on the Caney Fork River

than for Sites 1 and 2. Habitat reduction is related to increased average depth at Site 3 compared with the other two sites. Water depth is too great in most cells under all discharge conditions for sculpin.

101. Time-varying analysis of banded sculpin habitat reveals two important considerations that are not apparent under steady-state analyses. First, substantial habitat for the sculpin is available at some transects during the rising and falling arm of the peaking hydrograph with habitat minima occurring during both generation releases and during minimum low flows. Second, the downstream impacts of generation are reduced as the peaking wave attenuates during its downstream passage. Consequently, changes in habitat over the generation cycle become increasingly dampened with downstream distance. In fact, for banded sculpin, Site 3 probably represents the approximate downstream limit of peaking hydropower impact for nonriffle areas. In terms of the SDC, Site 3 can be envisioned as the "reset" distance suggested by Ward and Stanford (1983) and required to overcome the impacts of impoundment for banded sculpin.

Rainbow trout

102. At Site 1, minimal habitat is available for rainbow trout (Figure 38; note: the scale of WUA values is half that of the banded sculpin predictions). Contrary to previous analyses of trout habitat under peaking conditions (Curtis, Nestler, and Martin 1987; Nestler et al., in preparation), habitat availability increases with the rising limb of the peaking wave and declines during the falling limb. As noted previously, suitability criteria for rainbow trout in the Caney Fork were unusual in that velocity preferences were higher than expected, being optimum at velocities from 40 to 65 cm/sec. Thus, at low flows, velocity criteria are violated in almost all cells. With the rising limb of the peaking wave, increases in wetted area with concomitantly higher velocities result in increased WUA predictions (compare Figures 13, 14, and 15).

103. The trend of increased habitat availability with increasing discharge continues at Sites 2 and 3 (Figures 39 and 40). Again, increases in the size of wetted area and higher velocities associated with generation result in increases in predicted habitat. Substantially more habitat is available at Site 2, since this area is very broad and shallow at low flows and contains considerable medium velocity areas at high flows (Figures 20 and 22). At some transects, there is a decrease in usable habitat at the

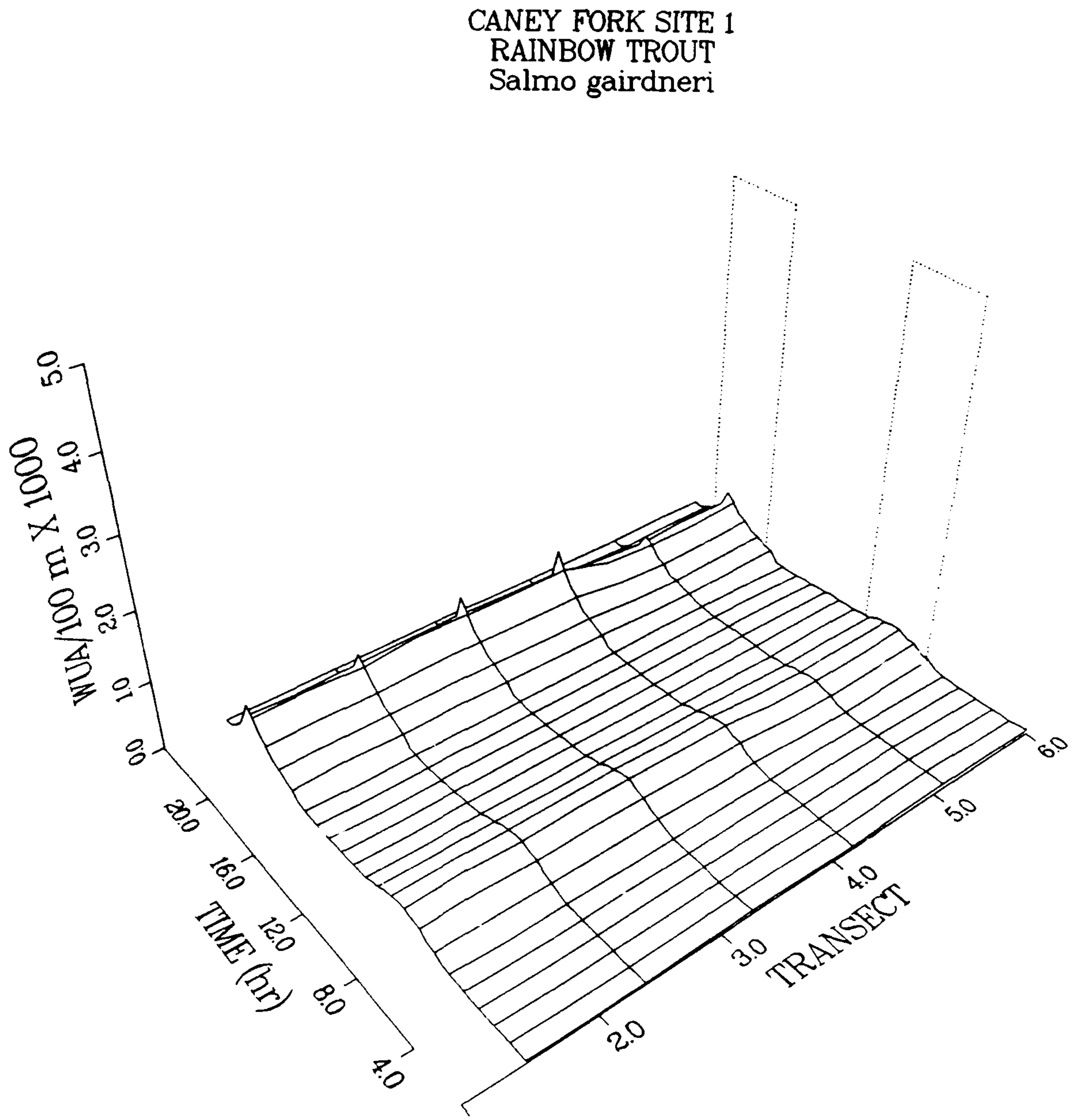


Figure 38. For adult rainbow trout (*Salmo gairdneri*) WUA/100 m of stream versus time versus river mile for Site 1 on the Caney Fork River

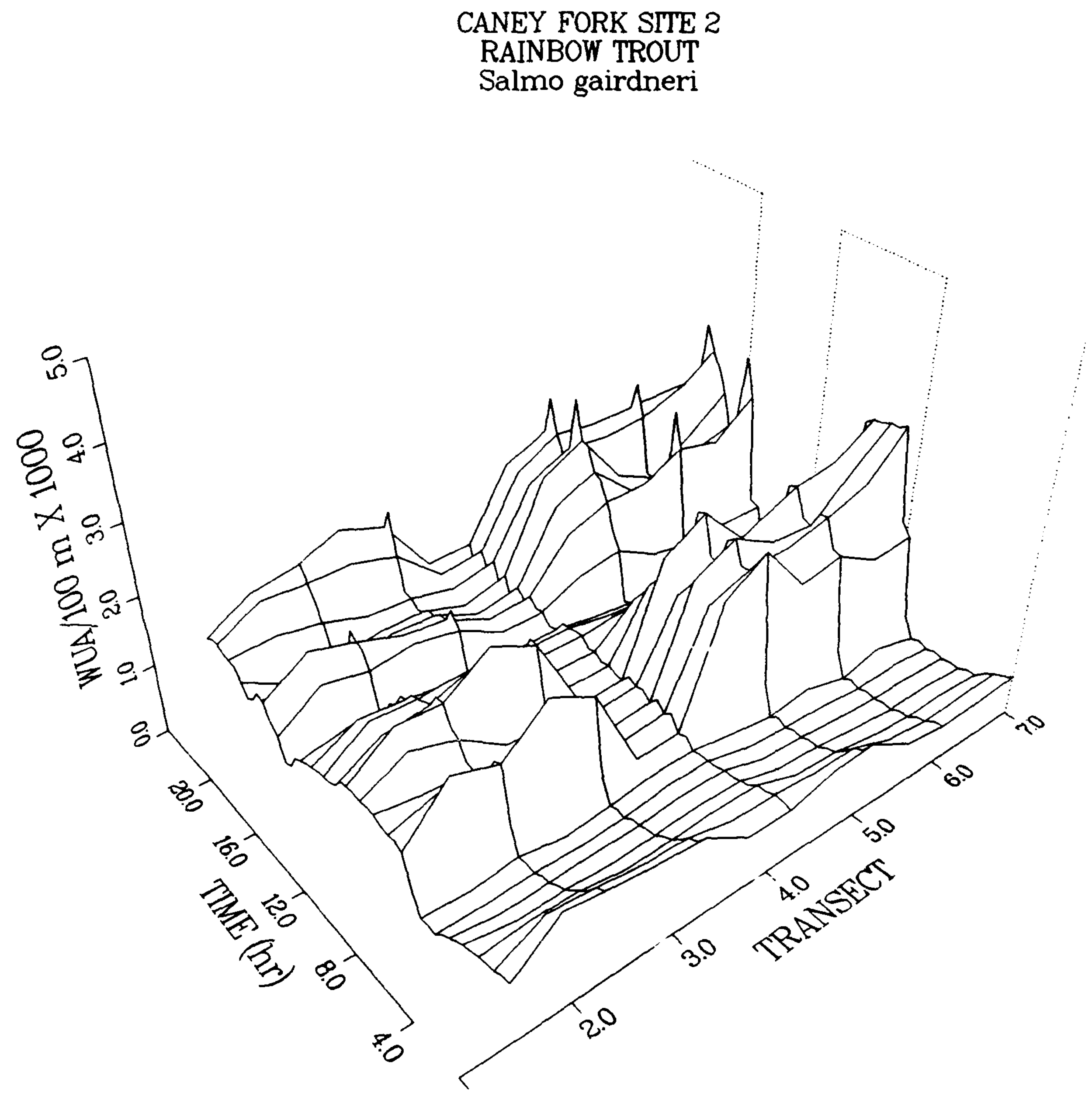


Figure 39. For adult rainbow trout (*Salmo gairdneri*), WUA/100 m of stream versus time versus river mile for Site 2 on the Caney Fork River

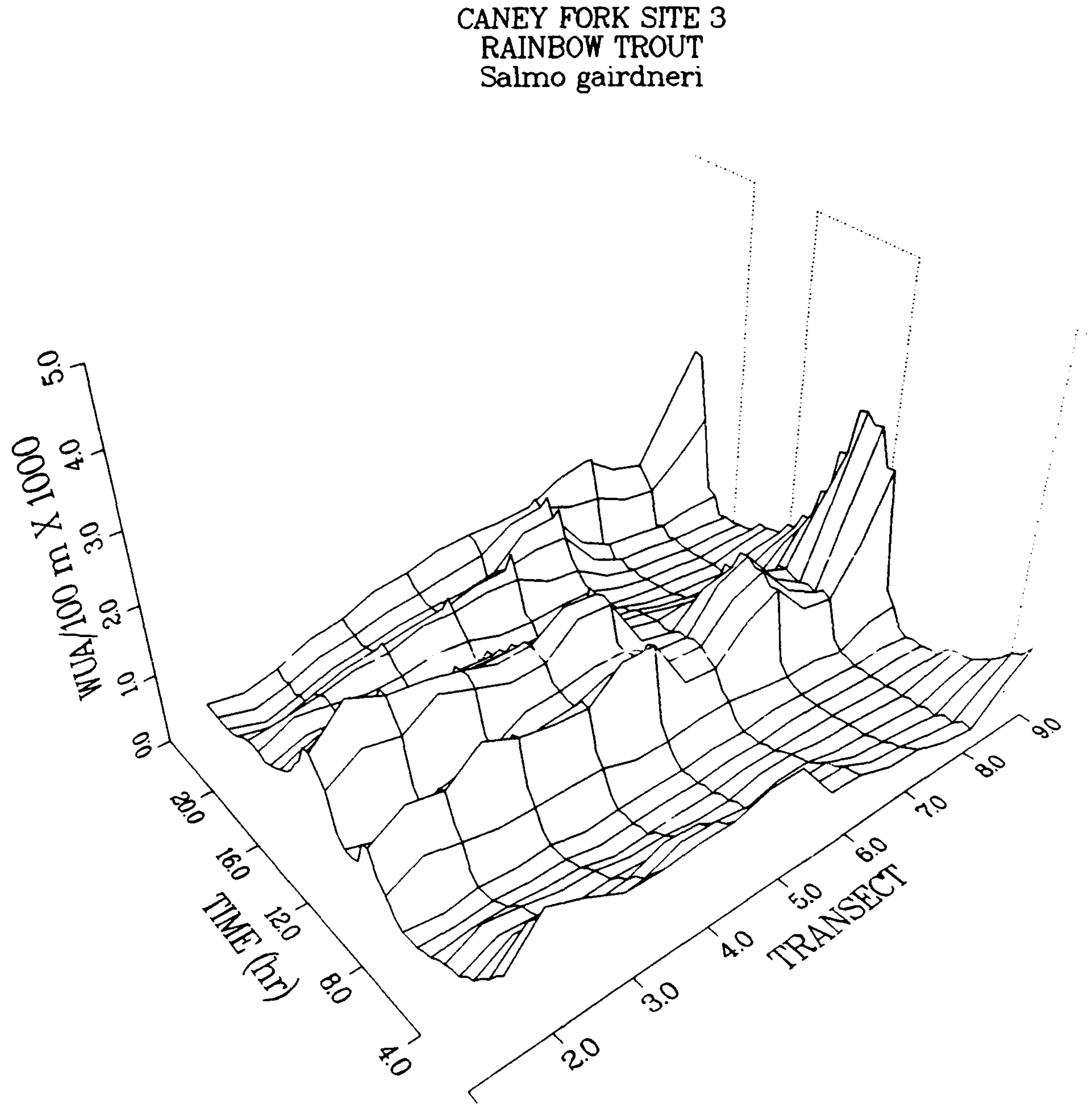


Figure 40. For adult rainbow trout (*Salmo gairdneri*), WUA/100 m of stream versus time versus river mile for Site 3 on the Caney Fork River

highest discharges during the peaking release; for example, Transects 3 and 6 at Site 2 and Transects 1 through 5 at Site 3. Velocities at these cross sections considerably exceed optimum velocities producing reduced habitat predictions.

PART VII: CONCLUSIONS

General Conclusions

104. The modified IFIM procedures used to simulate habitat changes for banded sculpin and rainbow trout represent an advance in the state of the art and provide a vehicle for describing, in greater detail than previously possible, habitat considerations downstream of peaking hydropower projects. The considerations include habitat changes occurring during the rising and falling limb of the hydrograph, changing downstream hydraulic conditions as the peaking wave attenuates in its passage through the tailwater, and the importance of considering the time delay of the peak as it moves downstream. The modified IFIM used in this report presents the most defensible description of downstream peaking hydropower impacts currently available, and its use is recommended to explore and assess the impacts of power generation.

Limitations and Considerations

105. Unfortunately, like all models (Gore and Nestler 1988), the IFIM has inherent limitations that preclude complete assessment of impact. Most prominently, output of IFIM is restricted to predictions of habitat and not biomass or number. Prediction of density requires interweaving the IFIM with population models. Examples of instream flow studies using IFIM that include population models can be found in Bovee and Zuboy (1988).

106. In addition to limitations in predicting biomass he formulation of IFIM used in this study has several other limitations, some of which have been addressed in the latest version of the PHABSIM system (Milhous et al., in press). Specific programs from the latest version of PHABSIM will be identified where appropriate. First, the precise biological significance of the rapid rise and fall of habitat availability predicted during a generation cycle (see Figures 34-36) is not completely known. That is, are these temporary gains and losses of habitat a physical condition to which biota can respond, or are the rapid changes in depths, velocities, and shear stresses conditions that must be endured in "hydraulic refuges"? If the latter, then new suitability criteria, termed hydraulic refuge criteria, must be substituted into the appropriate habitat evaluation subroutines (HABTAT, HABEF,

etc.) during the rising limb of the generation curves.

107. In fact, preliminary analyses of ongoing telemetry study indicate that rainbow trout do indeed seek out hydraulic refuges. Moreover, the data suggest that suitability criteria developed during low-flow conditions may not be appropriate for application during generation periods.

108. The second limitation of the formulation of IFIM used in this study relates to its inability to realistically portray the milieu of hydraulic conditions preferred by fishes. Observations made during this study and by others (Beecher 1987) indicate that many fishes, including sculpins, prefer relatively quiescent conditions bordered by faster water. This "feeding station" behavior is difficult to simulate using common approaches within the IFIM since suitability criteria are created treating each cell individually without considering flow conditions in adjacent cells. However, the HABTAV program in the latest release version of PHABSIM can be used to evaluate flow conditions in neighboring cells. Other limitations presented in this discussion will be addressed in the future as part of ongoing work in this research area.

Habitat Conditions for Banded Sculpin

109. Analysis of the biological meaning of short-term gains and losses in habitat during the generation period is difficult since little is known of the instantaneous response of banded sculpin to rapid changes in flow. Field observations of sculpin species generally indicate that sculpins are fairly immobile and would not likely relocate frequently over great distances to track optimum habitat if local hydraulic conditions became unacceptable (Greenberg and Holtzman 1987). Thus, habitat improvement for banded sculpin during the rising limb of the hydrograph should be considered only in those cells that contained usable habitat at low flows. This alteration would have the effect of eliminating habitat gains during the rising and falling limbs of the peaking hydrograph (produced from watering of previously dry areas).

110. Restricting from the analysis those cells that are dewatered during low flow improves the biological realism of the analysis; however, it still does not consider the significance of rapid changes in habitat for the remaining cells. A closer evaluation of field observations for banded sculpin provides further insight to this question. Hunt, Niemaela, and Layzer (1988),

Finger (1982), and Greenberg and Holtzman 1987 have all demonstrated that individual sculpins occupy low-velocity areas flanked (within one or two body lengths) by high velocities (Table 3). Thus, the complex hydraulics resulting from changes in velocity and depth associated with peaking hydropower operation are of little importance to the sculpin as long as substrate is available with sufficient roughness to provide velocity refuges. Through this behavior, sculpins are insulated from most of the effects of rapid flow changes associated with peaking operation. Indeed, this behavior probably accounts for their high abundances in tailwaters of peaking hydropower projects.

Table 3

Results of Tukey's Multiple Range Test Comparing Mean Bottom Velocities at Locations Where Sculpin Were Observed with Surrounding Bottom Velocities One Fish Length Away from Sculpins

Location	Velocity, cm/sec*		
Sculpin location	9	A	
Downstream	13	A	B
Upstream	14		B
Left	16		B
Right	17		B

* Means referenced by the same letter do not differ significantly.

111. Sculpins may alter their behavior during the generation cycle. During low flows, their position downstream of obstructions in the stream may serve as the center of foraging activities. During the rising limb of the peaking wave, when shear stresses increase, these same positions may serve as velocity refuges.

PHABSIM Modifications for Banded Sculpin

112. The following approaches and modifications to PHABSIM are required to simulate the habitat requirements of banded sculpins based on field observations of their behavior and literature information. The approaches used for sculpins could be expanded for use on other benthic fishes. These changes and additions to PHABSIM will be evaluated and documented in a later report.

a. Habitat predictions are restricted only to those cells inundated during low flows. Cells dewatered during low flow probably provide limited habitat at higher flows because of the limited mobility of sculpin.

b. To estimate refuge habitat values of cells during peaking releases, refuge suitability curves should replace habitat suitability curves in the analysis during the rising limb of the peaking hydrograph until maximum flows return to low stages. Investigators at the US Army Engineer Waterways Experiment Station (WES) suggest that refuge habitat be based on velocity criteria that have a suitability of 1.0 over their entire range and depth criteria that have a suitability of 0.0 from a depth of 0.0 to a depth of 15 cm and a suitability of 1.0 for all depths greater than 15 cm. Substrate/cover criteria should remain the same as under low-flow conditions.

c. The HABTAT program of PHABSIM is modified to allow routine evaluation of flow in combinations of cells to allow simulation of "feeding stations" and other complex fish behaviors to increase model realism or utilize the HABTAV program in the latest release version of PHABSIM (Milhous et al., in preparation).

113. The final step in an instream flow study is to relate habitat values to estimates of density. Predictions of density require incorporation of a population modeling into the fabric of the instream flow study. Although this final step increases the realism of the analysis, it is also very specific to the species and site being investigated. In most cases, instream flow studies do not address this final step because of the time and expense involved.

Habitat Conditions for Rainbow Trout

114. As with the PHABSIM output for the banded sculpin, interpretation of the results of the physical habitat simulation is difficult. It would appear that habitat availability increases with the peaking releases. However, the WES ongoing telemetry studies suggest that rainbow trout seek out different hydraulic conditions during periods of generation. The response of trout to an increase in discharge is rapid.* Typically, radio-tagged trout occupying a cell adjacent to a cell with cover will move laterally into the adjacent cell as stage increases. However, many tagged fishes during low flow occupy cells

---

* Personal Communication, 1988, S. Niemala and J. B. Layzer, Tennessee Cooperative Fishery Research Unit, US Fish and Wildlife Service, Cookeville, TN.

that are a considerable distance away from the nearest cover. During a peaking release, these fishes are more apt to move greater distances (up to 300 m) to find a hydraulic refuge. Often, an individual fish will move to the same refuge that it occupied during a previous peaking release. Once fishes reach an hydraulic refuge, there is little further movement, perhaps because adjacent cells with high velocity are physiologically stressful.

115. Complete analysis of the results of the WES telemetry study will provide considerable insight into the biological value of the short-term gains and losses of habitat for rainbow trout. A cursory analysis of the data collected to date suggests that some of the gains in usable habitat are not utilized by trout even though the trout are more mobile than banded sculpin. Moreover, most of the hydraulic refuges used by trout during peaking releases are dewatered during low flows. Thus, the determination of usable habitat for rainbow trout during peaking releases must include areas that are dewatered during low-flow periods. This is in marked contrast with the suggestion of excluding these areas from consideration in determining usable habitat for banded sculpin.

PHABSIM Modifications for Rainbow Trout

116. Behavioral studies suggest that hydraulic refuges are extremely important to rainbow trout during high-velocity periods. Although hydraulic refuges are important for both sculpin and trout, the greater mobility of trout suggests that different modifications to PHABSIM are needed for trout compared with those suggested for benthic fishes such as banded sculpin.

a. Based on the preliminary data of Hunt, Niemala, and Layzer (1988), those cells that are adjacent to cells which contain at least 25-percent cover should be given higher suitability values than cells of the same hydraulic condition but not adjacent to cells with cover. These weights should be applied during low-flow periods.

b. At high flows, the cells with high-cover values and adjacent to cells of at least 50-percent suitability should be evaluated as optimum refuge habitat during the peaking release period.

c. Those cells that are dewatered during low flows but that contain suitable cover at high flows should receive a high suitability (though not necessarily optimal) rating as refuge habitat during the peaking release period.

117. These recommendations are preliminary and await the results of radiotelemetry tracking of rainbow trout during peaking releases (in

progress).* Additional important habitat factors may come to light as WES investigators further evaluate the instantaneous response of trout to the rising arm of the generation wave, examine for temporal changes in response, and determine the importance of neighbor-cell characteristics on cell selection by trout.

Summary

118. The following conclusions and findings were made in this study.

a. Major impacts that occur in reservoir tailwaters result from changes in thermal regime, water quality, and hydrologic conditions. The most severe downstream thermal and water quality impacts are most often associated with deep-release projects.

b. Adequate description and assessment of impoundment require use of the concepts in two of the major paradigms of aquatic ecology, the HSEC and the RCC (and its conceptual progeny the SDC).

c. Peaking hydropower projects exhibit downstream impacts related to substantial daily flow fluctuations that are in addition to the impacts of nonhydropower projects.

d. Flow conditions in the immediate tailwater of peaking facilities alternate between generation releases and minimum low flows. Channel degradation and armoring often produce a simple channel characterized by a tendency towards uniform flow conditions in the immediate tailwater. Degradation and armoring decrease downstream until zones of aggradation occur. Concomitantly, flow conditions become less uniform and habitat diversity increases.

e. The IFIM, with some modifications, serves as a suitable conceptual framework to describe habitat considerations in CE reservoir tailwaters. The IFIM is particularly suited to describe habitat impacts downstream of peaking hydropower projects because of its use of detailed flow descriptions.

f. The modified IFIM presented in this report is recommended as an improved means of assessing the impacts of highly varying releases on downstream aquatic biota.

g. Based on the research presented in this report and results of continuing studies, several modifications to PHABSIM are recommended to increase the realism of IFIM simulations. The revisions will be evaluated and documented in a later report.

---

* Personal Communication, 1988, S. Niemala and J. B. Layzer, Tennessee Cooperative Fishery Research Unit, US Fish and Wildlife Service, Cookeville, TN.

REFERENCES

Anderson, K. G., Bronmark, C., Herrman, J., Malmqvist, B., Otto, C., and Sjostrom, P. 1986. "Presence of Sculpin (*Cottus gobio*) Reduces Drift and Activity of *Gammarus pulex* (Amphipoda)," Hydrobiologia, Vol 133, pp 209-215.

Bachman, R. A. 1984. "Foraging Behavior of Free-Ranging Wild and Hatchery Brown Trout in a Stream," Transactions of the American Fisheries Society, Vol 113, pp 1-32.

Bain, M. B., Finn, J. T., and Booke, H. E. 1988. "Streamflow Regulation and Fish Community Structure," Ecology, Vol 69, pp 382-392.

Baxter, R. M. 1977. "Environmental Effects of Dams and Impoundments," Annual Review of Ecology and Systematics, Vol 8, pp 255-283.

Baxter, R. M., and Glaude, P. 1980. "Environmental Effects of Dams and Impoundments in Canada: Experience and Prospects," Canadian Bulletin of Fisheries Aquatic Science, No. 205.

Bedford, K. W., Sykes, R. M., and Libicki, C. 1983. "Dynamic Advective Water Quality Model for Rivers," Journal of Environmental Engineering Division, American Society of Civil Engineers, Vol 109, pp 535-545.

Beecher, H. A. 1987. "Simulating Trout Feeding Stations in Instream Flow Models," J. S. Craig and J. B. Kemper, eds., Regulated Streams: Advances in Ecology, Plenum Press, New York, pp 71-82.

Bovee, K. D. 1978. "Probability-of-Use Criteria for the Family Salmonidae," Instream Flow Information Paper No. 4, FWS/OBS-78/07, US Fish and Wildlife Service, Washington, DC.

__________. 1982. "A Guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology," Instream Flow Information Paper No. 12, FWS/OBS-82/26, US Fish and Wildlife Service, Washington, DC.

__________. 1985. "Evaluation of the Effects of Hydropeaking on Aquatic Macroinvertebrates Using PHABSIM," in: F. W. Olson, R. G. White, and R. H. Hamre, eds., Symposium on Small Hydropower and Fisheries, American Fisheries Society, Bethesda, MD, pp 236-241.

__________. 1986. "Development and Evaluation of Habitat Suitability Criteria for Use in the Instream Flow Incremental Methodology," FWS/OBS-86/7, US Fish and Wildlife Service, Washington, DC.

Bovee, K., and Zuboy, J. R., eds. 1988. "Proceedings of a Workshop on the Development and Evaluation of Habitat Suitability Criteria," Biology Report 88(11), US Fish and Wildlife Service, Washington, DC.

Brocksen, R. W., Fraser, M., Murarka, I., and Hildebrand, S. G. 1982. "The Effects of Selected Hydraulic Structures on Fisheries and Limnology, CRC Critical Review in Environmental Control, pp 69-89.

Cada, G. F., Sale, M. J., Cushman, R. M., and Loar, J. M. 1983. "Field Test of a Biological Assumption of Instream Flow Models," Report No. CONF-830939-3, Oak Ridge National Laboratory, Oak Ridge, TN.

C-irns, J., Jr., Benfield, E. F., and Webster, J. R., eds. 1978. "Current Pei pectives on River-Reservoir Ecosystems," North American Benthology Society, Special Publication.

Craig, J. F., and Kemper, J. B., eds. 1987. Regulated Streams: Advances in Ecology, Plenum Press, New York.

Curtis, L. T., Nestler, J. M., and Martin, J. L. 1987. "Comparative Effects on Trout Habitat of Hydropower Modification With and Without Reregulation in the Cumberland River Below Wolf Creek Dam, Kentucky," Miscellaneous Paper E-87-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cushman, R. M. 1985. "Review of Ecological Effects of Rapidly Varying Flows Downstream from Hydroelectric Facilities," North American Journal of Fisheries Management, Vol 5, pp 330-339.

Dufford, R. G., Zimmerman, H. J., Cline, L. D., and Ward, J. V. 1987. "Responses of Epilithic Algae to Regulation of Rocky Mountain Streams," in: J. F. Craig and J. B. Kemper, eds., Regulated Streams: Advances in Ecology, Plenum Press, New York.

Fast, A. W., and Holquist, R. G. 1982. "Supersaturation of Nitrogen Gas Caused by Artificial Aeration in Reservoirs," Technical Report E-82-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fausch, K. D. 1984. "Profitable Stream Positions for Salmonids: Relating Specific Growth Rate to Net Energy Gain," Canadian Journal of Zoology, Vol 62, pp 441-451.

Fausch, K. D., and White, R. J. 1981. "Competition Between Brook Trout (*Salvelinus fontinalis*) and Brown Trout (*Salmo trutta*) for Positions in a Michigan Stream," Canadian Journal of Fish and Aquatic Science, Vol 38, pp 1220-1227.

Finger, T. R. 1982. "Interactive Segregation Among Three Species of Sculpins (*Cottus*)," Copeia, pp 680-694.

Flecker, A. S. 1984. "The Effects of Predation and Detritus on the Structure of a Stream Insect Community: A Field Test," Oecologia, Vol 64, pp 300-305.

Fraley, J., and Decker-Hess, J. 1987. "Effects of Stream and Lake Regulation on Reproductive Success of Kokanee in the Flathead River System, Montana, U.S.A." Regulated Rivers: Research and Management, Vol 1, pp 257-265.

Gislason, J. C. 1985. "Aquatic Insect Abundance in a Regulated Stream Under Fluctuating and Stable Diel Flow Patterns," North American Journal of Fisheries Management, Vol 5, pp 39-46.

Gordon, J. A. 1979. "Temperature and Hydrodynamic Predictions for Center Hill Lake Using the LARM Two-Dimensional Computer Model," US Army Engineer District Nashville, Nashville, TN.

Gore, J. A. 1977. "Reservoir Manipulations and Benthic Macroinvertebrates in a Prairie River," Hydrobiologia, Vol 55, pp 113-123.

__________. 1980. "Ordinational Analysis of Benthic Communities Upstream and Downstream of a Prairie Storage Reservoir," Hydrobiologia, Vol 69, pp 33-44.

Gore, J. A., and Judy, R. D., Jr. 1981. "Predictive Models of Benthic Macroinvertebrate Density for Use in Instream Flow Studies and Regulated Flow Management," Canadian Journal of Fisheries and Aquatic Science, Vol 38, pp 1363-1370.

Gore, J. A., and Nestler, J. M. 1988. "Instream Flow Studies in Perspective," Regulated Rivers: Research and Management, Vol 2, No.2, pp 93-101.

Gore, J. A., Nestler, J. M., and Layzer, J. B. 1988. "Instream Flow Predictions and Management Options for Biota Affected by Peaking Hydropower Releases," Fourth International Symposium on Regulated Streams, Loughborough, England.

Gore, J. A., and Pennington, W. 1988. "Changes in Larval Chironomid Habitat with Distance from Peaking Hydropower Operations," Bulletin of the North American Benthology Society, Vol 5, pp 100.

Gore, J. A., and Petts, G. E., eds. In press. Alternatives in Regulated River Management, Submitted to CRC Press, Inc., for publication, Boca Raton, FL.

Greenberg, L. A., and Holtzman, D. A. 1987. "Microhabitat Utilization, Feeding Periodicity, Home Range and Population Size of the Banded Sculpin, *Cottus carolinae*," Copeia, pp 19-25.

Hershey, A. E., and Dodson, S. I. 1985. "Selective Predation by a Sculpin and a Stonefly on Two Chironomids in Laboratory Feeding Trials," Hydrobiologia, Vol 124, pp 269-273.

Holmes, N. T. H., and Whitton, B. A. 1981. "Phytobenthos of the River Tees and Its Tributaries," Freshwater Biology, Vol 11, pp 139-163.

Hunt, T. D., Niemala, S. L., and Layzer, J. B. 1988. "Habitat Suitability Criteria Developed from Underwater Observations of Fish in a Peaking Hydroelectric Tailwater," Fourth International Symposium on Regulated Streams, Loughborough, UK.

Jacobs, K. E., et al. 1985. "Fish Recruitment and Movement in a Flood Control Reservoir," Technical Report E-85-15, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Johnson, B. H. 1983. "User's Guide for Branched Implicit River Model (BIRM) with Application to the Lower Mississippi River," US Army Engineer Waterways Experiment Station, Vicksburg, MS

King, J. M., Day, J. A., Hurly, P. R., Henshall-Howard, M., Davies, B. R., and McQuinn, I. H. In Press. "Invertebrate Communities and Correlated Environmental Variables in a Southern African Mountain Stream: Functional Feeding Groups and Numerical Analyses," Submitted to Canadian Journal of Fisheries and Aquatic Science, for publication.

Kondratieff, B. C., and Voshell, J. R., Jr. 1981. "Influence of a Reservoir with Surface Release on the Life History of the Mayfly *Heterocloen curiosum* (McDunnough) (Ephemeroptera: Baetidae)," Canadian Journal of Zoology, Vol 59, pp 305-314.

Layzer, J. B., Nehus, T. J., Pennington, W., Gore, J. A., and Nestler, J. M. 1988. "Seasonal Variation in the Composition of the Drift Below a Peaking Hydro-Electric Project," Fourth International Symposium on Regulated Streams, Loughborough, UK.

Lillehammer, A., and Saltveit, S. J., eds. 1984. Regulated Rivers, Universitetsforlaget AS, Oslo.

Martin, J. L., Curtis, L. T., and Nestler, J. M. 1985. "Effects of Flow Alterations on Trout Habitat in the Cumberland River Below Wolf Creek Dam," Miscellaneous Paper E-86-11, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Matter, W. J., Hudson, P. L., and Saul, G. E. 1983. "Invertebrate Drift and Particulate Organic Material Transport in the Savannah River Below Lake Hartwell During a Peak Power Generation Cycle," in: T. P. Fontaine and S. M. Bartell, eds., Dynamics of Lotic Ecosystems, Ann Arbor Science Publishers, Ann Arbor, MI.

Matter, W. J., Nestler, J. M., and Saul, G. E. 1983. "Movement, Transport, and Scour of Particulate Organic Matter and Aquatic Invertebrates Downstream from a Peaking Hydropower Project," Technical Report E-83-12, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Milhous, R. T. 1986. "The Use of One Velocity Calibration Data Set with IFG4," PHABSIM Technical Note No. 4, US Fish and Wildlife Service," Washington, DC.

Milhous, R. T., Updike, M. A., and Schneider, D. M. 1989. "Computer Reference Manual for the Physical Habitat Simulation System (PHABSIM) Version II," NERC 89, US Fish and Wildlife Service, Washington, DC.

Nestler, J. M. 1987. "Problems in Applying IFIM to Warmwater River Ecosystems, Workshop on Application of Instream Flow Methologies to Warmwater Fisheries," Technical Aquatic Biological Station, American Fisheries Society, Warm Water Fisheries Division, Cookeville, TN.

Nestler, J. M., Gore, J. A., Curtis, L. T., and Martin, J. L. "Predicted Effects of Hydropower Uprate on Trout Habitat in the Cumberland River Downstream of Wolf Creek Dam, Kentucky," Miscellaneous Paper in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nestler, J. M., Milhous, R. T., and Layzer, J. B. In Press. "Instream Habitat Modeling Techniques for Fish," in: J. A. Gore and G. E. Petts, eds., Alternatives in Regulated River Management, Submitted to CRC Press, Inc., for publication, Boca Raton, FL.

Nestler, J. M., Milhous, R. T., Troxel, J., and Fritschen, J. A. 1986a. "Effects of Flow Alterations on Trout, Angling, and Recreation in the Chattahoochee River, Between Buford Dam and Peachtree Creek," Technical Report E-86-10, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nestler, J. M., Walburg, C. H., Novotny, J. F., Jacobs, K. E., and Swink, W. D. 1986b. "Handbook on Reservoir Releases for Fisheries and Environmental Quality," Instruction Report E-86-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Odenkirk, J. S. 1987. "Food Habits of Rainbow Trout and Seasonal Abundance of Aquatic Macroinvertebrates in the Center Hill Tailwater," MS Thesis, Tennessee Tech University, Cookeville, TN.

Petts, G. E. 1984. Impounded Rivers: Perspectives for Ecological Management, John Wiley and Sons, Chichester.

Reiser, D. W., Ramey, M. P., and Wesche, T. A. In Press. "Flushing Flows," in: J. A. Gore and G. E. Petts., eds., Alternatives in Regulated River Management, Submitted to CRC Press, Inc., for publication, Boca Raton, FL.

Ross, L. E., and Rushforth, S. R. 1980. "The Effects of a New Reservoir on the Attached Diatom Communities in Huntington Creek, Utah, USA," Hydrobiologia, Vol 68, pp 157-165.

Scarnecchia, D. L. 1988. "The Importance of Streamlining in Influencing Fish Community Structure in Channelized and Unchannelized Reaches of a Prairie Stream," Regulated Rivers, Vol 2, pp 155-166.

Schwoerbel, J. 1967. "Das Hyporehiesche Interstitial als Grenzbiotop Zwischen Oberirdischem und Subteranem Okosystem und Seine Bedeutung fur die Primar-Evolution von Kleinstholenbewohnern," Archaeological Hydrobiology/Supplement, Vol 33, pp 1-62.

Stalnaker, C. B. 1982. "Instream Flow Assessments Come of Age in the Decade of the 1970s," in: W. T. Mason, Jr., and S. Iker, eds., Research on Fish and Wildlife Habitat, EPA-600/8-82-022, US Environmental Protection Agency, pp 119-142.

Statzner, B. 1987. "Characteristics of Lotic Ecosystems and Consequences for Future Research Directions," in: Ecological Studies, Vol 61, Springer-Verlag, Berlin, pp 366-390.

Statzner, B., Gore, J. A., and Resh, V. H. In Press. "Hydraulic Stream Ecology: Observed Patterns and Potential Application," Submitted to Journal of North American Benthology Society, for publication.

Statzner, B., and Higler, B. 1985. "Questions and Comments on the River Continuum Concept," Canadian Journal of Fisheries and Aquatic Science, Vol 42, pp 1038-1044.

__________. 1986. "Stream Hydraulics as a Major Determinant of Benthic Invertebrate Zonation," Freshwater Biology, Vol 16, pp 127-139.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., and Cushing, C. E. 1980. "The River Continuum Concept," Canadian Journal of Fisheries and Aquatic Science, Vol 37, pp 130-137.

Walburg, C. H., Novotny, J. F., Jacobs, K. E., and Swink, W. D. 1983. "Effects of Reservoir Release on Water Quality, Macroinvertebrates, and Fish in Tailwaters: Field Study Results," Technical Report E-83-6, prepared by National Reservoir Research Program, US Fish and Wildlife Service, for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walburg, C. H., Novotny, J. F., Jacobs, K. E., Swink, W. D., Campbell, T. M. Nestler, J. M., and Saul, G. E. 1981. "Effects of Reservoir Releases on Tailwater Ecology: A Literature Review," Technical Report E-81-12, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Ward, J. V. 1974. "A Temperature-Stressed Stream Ecosystem Below a Hypolimnial Release Mountain Reservoir," Archaeological Hydrobiology, Vol 74, pp 247-275.

__________. 1976. "Comparative Limnology of Differentially Regulated Sections of a Colorado Mountain River," Archaeological Hydrobiology, Vol 78, pp 319-342.

Ward, J. V., and Stanford, J. A., eds. 1979. The Ecology of Regulated Streams, Plenum Press, New York.

Ward, J. V., and Stanford, J. A. 1983. "The Serial Discontinuity Concept of Lotic Ecosystems," in: Fontaine and Bartelle, eds., Dynamics of Lotic Ecosystems, Ann Arbor Science Publishers, Ann Arbor, MI, pp 29-42.

White, R. G., and Wade, D. T. 1980. "A Study of Fish and Aquatic Macroinvertebrate Fauna in the South Fork Boise River Below Anderson Ranch Dam with Emphasis on Effects of Fluctuating Flows," Compl. Report 14-06-100-9220, Contract No. 191, Forest Wildlife Range Experiment Station, University of Idaho, Moscow, ID.

Wiltzbach, M. A. 1985. "Relative Roles of Food Abundance and Cover in Determining the Habitat Distribution of Stream-Dwelling Cutthroat Trout (*Salmo clarki*)," Canadian Journal of Fisheries and Aquatic Science, Vol 42, pp 1668-1672.

Winterbourn, M. J., Rounick, J. S., and Cowie, B. 1981. "Are New Zealand Stream Ecosystems Really Different?" New Zealand Journal of Marshes and Freshwater Science, Vol 15, pp 321-328.

Zale, A. V., and Neves, R. J. 1982. "Fish Hosts of Four Species of Lampsilinae Mussels (Mollusca: Unionidae) in Big Moccasin Creek, Virginia," Canadian Journal of Zoology, Vol 60, pp 2535-2542.